Timing and Evolution of Structures within the Southeastern Greater Caucasus and Kura Fold-Thrust Belt from Multiproxy Sediment Provenance Records

Adam M. Forte[1] (aforte8@lsu.edu), Eric S. Cowgill[2] (escowgill@ucdavis.edu), Dawn Y. Sumner[2] (dysumner@ucdavis.edu) Dominique I. Garello[1] (dgarello1@lsu.edu), Nathan A. Niemi[3] (naniemi@umich.edu), K. Colton Fowler[1] (kfowl11@lsu.edu)

[1]Department of Geology & Geophysics, Louisiana State University, Baton Rouge, LA, USA
[2]Department of Earth and Planetary Sciences, University of California, Davis, CA, USA
[3]Department of Earth & Environmental Sciences, University of Michigan, Ann Arbor, MI, USA

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Adam M. Forte[1], Eric S. Cowgill[2], Dawn Y. Sumner[2], Dominique I. Garello[1], Nathan A. Niemi[3], K. Colton Fowler[1]

[1]Department of Geology & Geophysics, Louisiana State University, Baton Rouge, LA, USA
[2]Department of Earth and Planetary Sciences, University of California, Davis, CA, USA
[3]Department of Earth & Environmental Sciences, University of Michigan, Ann Arbor, MI, USA

ABSTRACT

The Greater Caucasus (GC) mountains are the locus of post-Pliocene shortening within the north central Arabia-Eurasia collision. Although recent low-temperature thermochronology constrains the timing of orogen formation, the evolution of major structures remains enigmatic - particularly regarding the internal kinematics within this young orogen and the associated Kura Fold-Thrust Belt (KFTB), which flanks its southeastern margin. Here we use a multiproxy provenance analysis to investigate the tectonic history of both the southeastern GC and KFTB by presenting new data from a suite of sandstone samples from the KFTB, including sandstone petrography, whole-rock geochemistry, and detrital zircon (DZ) U-Pb geochronology. To define source terranes for these sediments, we integrate additional new whole-rock geochemical analyses with published DZ results and geological mapping. Our analysis reveals an apparent discrepancy in up-section changes in provenance from the different methods. Sandstone

petrography and geochemistry both indicate a systematic up-section evolution from a volcanic/volcaniclastic source, presently exposed as a thin strip along the southeastern GC, to what appears similar to an interior GC source. Contrastingly, DZ geochronology suggests less up-section change. We interpret this apparent discrepancy to reflect the onset of sediment recycling within the KFTB, with the exhumation, weathering, and erosion of early thrust sheets in the KFTB resulting in the selective weathering of unstable mineral species that define the volcaniclastic source, but left DZ signatures unmodified. Using the timing of sediment recycling as a proxy for structural initiation of the central KFTB implies that the thrust belt initiated nearly synchronously along-strike at ~2.0-2.2 Ma.

1. INTRODUCTION AND MOTIVATION

The provenance histories of siliciclastic sedimentary rocks in foreland basins often provide a robust, and in some cases, singular record of the past structural and kinematic history of the flanking orogenic system (e.g., Sinclair, 1997; DeCelles et al., 1998; Lawton et al., 2010; Nagel et al., 2014; Leary et al., 2016; Capaldi et al., 2020). In detail, shifts in sediment provenance recorded in forelands can elucidate the order of initiation, direction of propagation, and style of structures within a mountain range, thus providing crucial constraints for tectonic models of orogen evolution (e.g., Carrapa et al., 2006; Panaiotu et al., 2007; Bande et al., 2012; Laskowski et al., 2013; Garber et al., 2020). The resulting information on both absolute and relative timing of structures can prove especially important in evaluating the extent to which particular mountain ranges obey the expected behavior of critically tapered orogenic wedges (e.g., Davis et al., 1983; Dahlen and Suppe, 1988; Dahlen, 1990). For example, critical wedge theory suggests a direct relationship between the efficiency of climate and the width of mountain ranges (e.g., Stolar et al., 2006; Whipple and Meade, 2006; Roe et al., 2008), where changes in width would in part be reflected in the order of initiation of structures and degree of temporal synchronicity of structural changes within the orogen and causative climatic changes. A potential example of this can be found in the Greater Caucasus (GC) and associated Kura Fold-Thrust Belt (KFTB; Figure 1), where some prior work suggested that initiation of the fringing fold-thrust belts, including the KFTB may reflect a climatically driven widening of the orogen after a shift to more arid conditions (e.g., Forte et al., 2013, 2022). Testing this hypothesis has in part been hindered by the relatively poor constraint on relative timing and along-strike patterns of initiation of individual structures within the range and foreland. Here we consider the extent to which sediment provenance can elucidate the structural history of both the southeastern GC and KFTB and help to resolve whether the growth of the KFTB was largely synchronous along-strike and is thus compatible with being driven by climatically induced widening of the orogen.

Specifically, while recent work by Trexler et al., (2022, 2023) has significantly clarified the locations, geometry, and nature of many of the first-order structures within the internal GC, the timing and evolution of these first-order structures remain under-constrained, with the exception of very specific locations in the western GC (Vasey et al., 2020) and extreme eastern GC (Tye et al., 2022). Similarly, while it is relatively well constrained that since initiation, portions of the KFTB have accommodated upwards of 50% of the orogen-perpendicular shortening between Arabia and Eurasia, and nearly all of the convergence between the Greater and Lesser Caucasus between 45-49°E (Forte et al., 2010, 2013), the exact timing of KFTB initiation and the extent to which the structures within the KFTB initiated diachronously or synchronously along-strike both remain unclear.

The formation of the KFTB is coincident with either a reduction in activity, or largescale abandonment, of the GC range front thrust(s) (e.g., Forte et al., 2010; Mosar et al., 2010) and represents a southward advance of the active thrust front by ~25-100 km, implying significant widening of the orogen, and simultaneous formation of the Alazani piggyback basin (Figure 1). As such, the formation of the KFTB reflects a significant structural reorganization within the southeastern GC (e.g., Forte et al., 2010; Mosar et al., 2010), and constraining the timing and evolution of deformation within the KFTB is critical for understanding the broader structural evolution of the GC and the context of this reorganization. For example, based on relatively limited data, Forte et al., (2013) originally hypothesized that initiation of the KFTB, and resultant widening of the GC, initiated at 1.5-1.8 Ma, coincident with regional records of an increase in aridity (e.g., Kvavadze and Vekua, 1993; Gabunia et al., 2000; Kovda et al., 2008; Messager et al., 2010a, 2010b). Forte et al., (2013) considered that this shift to more arid conditions could have initiated orogen widening and KFTB formation, consistent with the proposal that active, doubly-vergent orogens experiencing less efficient erosion will expand (Whipple and Meade, 2004, 2006). If orogenic widening driven by climatic forcing is a viable mechanism to explain the formation of the KFTB, this fundamentally predicts that initiation of the KFTB was synchronous along-strike.

While some prior work suggested a diachronous initiation of the KFTB along strike (Forte et al., 2010), recent constraints suggest a more synchronous initiation is viable, although these constraints come from the western and eastern termini of the belt (Figure 2; Forte et al., 2013;

Lazarev et al., 2019; Sukhishvili et al., 2021). The eastern KFTB initiated at ~2.1 Ma at the boundary between the Akchagylian and Apsheronian regional stages (Forte et al., 2013; Lazarev et al., 2019), and the western KFTB in the Gombori range initiated sometime between 2.7-1 Ma (Sukhishvili et al., 2021). To better understand the tectonic context of the KFTB it is necessary to establish the timing of the central KFTB and the relationship between thrust propagation and evolution of structures internal to the southeastern GC. Here we investigate these problems by tracking changes in provenance in the foreland sedimentary strata now exposed within the KFTB.

Prior work describing source terranes within the GC broadly suggest relatively distinct, thrust-bounded packages that have the potential to leave diagnostic signatures within the strata deformed by the KFTB (e.g., Cowgill et al., 2016; Tye et al., 2020). However, the previously available provenance data within the Kura Basin and associated KFTB region are limited and focused primarily on the oil-producing sandstones of the Productive Series at the eastern edge of the Kura Basin (Morton et al., 2003; Allen et al., 2006; Abdullayev et al., 2018) or on strata at its western and eastern ends, all of which are inferred to largely predate formation of the KFTB (Tye et al., 2020).

To explore the tectonic history of both the southeastern GC and KFTB, we present new detailed provenance analyses from Miocene-Pleistocene sedimentary rocks that are now exposed within the central portion of the KFTB. A majority of prior provenance work within the GC focuses on either detrital zircon (DZ) U-Pb geochronology (Allen et al., 2006; Cowgill et al., 2016; Abdullayev et al., 2018; Tye et al., 2020) or sandstone/modern sediment petrography or geochemistry (Vincent et al., 2013; Vezzoli et al., 2014, 2020). We build on this context and consider U-Pb ages from detrital zircons, sandstone composition from petrography, and bulk-sample major and trace element geochemical data. To compare source characterizations between DZ and geochemical and/or framework grain compositions, we supplement our foreland samples with additional geochemical analyses of both modern sediments from rivers draining the southern GC and northern Lesser Caucasus and Mesozoic-aged sandstone and volcanic rocks within the GC. With these data we specifically address the following questions: (1) how did the provenance of the northern Kura Basin evolve during the early growth of the GC; (2) what does the evolution of foreland provenance during this time suggest for structural evolution of the southeastern GC; and (3) does the provenance constrain the timing of KFTB initiation and along-strike evolution, and if so, did the belt initiate synchronously along-strike as predicted by models of climatic modulation of a bivergent orgogenic wedge?

The results of our multi-proxy approach reveal fundamental, and in many ways confusing, disconnects between implied provenance changes from geochemistry and petrography compared to detrital zircon geochronology. On the one hand, the geochemistry and petrography data suggest a general up-section shift from one GC-related source to another that appears to have occurred asynchronously across the basin. On the other hand, a more limited dataset of detrital zircon geochronology suggests effectively static sediment sourcing through time. We interpret this apparent discrepancy to result from sediment recycling, where the apparent up-section change in provenance inferred from the geochemical and petrographic data is a signal generated by selective weathering. Specifically, we infer that exhumation, exposure, weathering, and erosion of foreland basin sediments from thrust sheets within the KFTB led to selective weathering of components that are diagnostic of one of the key GC source terranes, and thus producing a signal that looks like a change in provenance. As a result, we argue that the onset of this sediment recycling signal is actually indicative of the timing of structural initiation of portions of the KFTB and thus helps to establish the timing and along-strike evolution of the KFTB and place it in tectonic context with the structural evolution of the southeastern GC.

2. BACKGROUND

2.1 Tectonic Setting

The GC are the main locus of Arabia-Eurasia convergence at their longitude and form the northern structural margin of the collision (Figure 1; e.g., Philip et al., 1989; Jackson, 1992; Allen et al., 2004; Dhont and Chorowicz, 2006; Reilinger et al., 2006). The range results from ongoing Cenozoic shortening that partially inverted a Jurassic-Cretaceous back-arc basin, which opened north of the Pontide-Lesser Caucasus (LC) island arc during north directed subduction of Neotethyan oceanic lithosphere (e.g., Adamia et al., 1977; Gamkrelidze, 1986; Zonenshain and Le Pichon, 1986; Cowgill et al., 2016; Vincent et al., 2016; van Hinsbergen et al., 2019; Vasey et al., 2021). Significant debate has centered on the early Cenozoic geometry and dimensions of the GC back-arc basin north of the LC (Cowgill et al., 2016, 2018; Vincent et al., 2016, 2018), but paleogeographic reconstructions constrain the NE-SW width to being between 200-400 km (van der Boon et al., 2018; van Hinsbergen et al., 2019; Darin and Umhoefer, 2022), similar to the dimensions of the Black Sea and South Caspian basins, which are likely remnants of the same back-arc basin system (Zonenshain and Le Pichon, 1986). Timing of initiation of closure and shortening of the GC back-arc basin is unclear, but had likely begun by the Eocene-

Oligocene (e.g., Vincent et al., 2007) and was accommodated in part by northward subduction of oceanic or transitional lithosphere, based on seismic evidence of a subducted slab in the eastern GC (Skolbeltsyn et al., 2014; Mumladze et al., 2015; Gunnels et al., 2020). The timing of the transition from subduction to collision and beginning of significant upper plate shortening and exhumation has also proven controversial, but recent new results from, and syntheses of, low-temperature thermochronology data have largely confirmed the original suggestion by Avdeev and Niemi (2011) of initiation of rapid exhumation between 10-5 Ma throughout much of the range (e.g., Vincent et al., 2020; Forte et al., 2022; Tye et al., 2022; Cavazza et al., 2023). Subsequently, active deformation and the locus of shortening at the surface has largely shifted to a series of fringing foreland fold-thrust belts in the northcentral and northwestern (Sobornov, 1994, 1996, 2021; Forte et al., 2014), southwestern (Banks et al., 1997; Tsereteli et al., 2016; Tibaldi et al., 2017, 2018, 2021; Trexler et al., 2020; Alania et al., 2021b), southcentral (Alania et al., 2021a), and southeastern (Forte et al., 2010, 2013, 2014; Alania et al., 2015) GC. The initiation of the majority of these fold-thrust belts are broadly constrained to occurring during the Plio-Pleistocene. Our focus here is on clarifying the initiation age of the southeastern fold thrust-belt, i.e., the KFTB.

2.2 Regional Geology

The geology of the central and eastern GC (Figure 1c) is dominated by Jurassic to Cretaceous shallow-marine carbonate rocks along the northern flank, Jurassic to Cretaceous flysch to molasse within much of the core of the orogen, and Jurassic to Cretaceous volcanic and volcaniclastic rocks along the southern flank (e.g., Saintot et al., 2006; Adamia et al., 2011a;

Forte et al., 2014; Cowgill et al., 2016; Tye et al., 2020). Three observations of the regional geology are particularly important with respect to sediment provenance and potential source terranes for sediments within the Kura foreland basin. First, within the GC, intrusive, metamorphic, and metasedimentary rocks predating Jurassic rifting in the GC back-arc basin are only exposed in the western GC (Undifferentiated Basement in Figure 1c; Saintot et al., 2006; Adamia et al., 2011a). Second, there are two geographically distinct sequences of predominantly Jurassic to Cretaceous volcanic and/or volcaniclastic rocks exposed along the southern margin of the GC, with the one in the west being more extensively exposed and having a wider cross-strike width than the one in the east; the latter is sometimes referred to as the Vandam zone and both are considered to be genetically linked with the similarly aged Pontide-Lesser Caucasus Arc (e.g., Kopp and Shcherba, 1985). Third, and finally, there are various small exposures of Paleozoic to Precambrian crystalline rocks within the Dzirula Massif (Zakariadze et al., 1998; Mayringer et al., 2011; Shengelia et al., 2012) and Lesser Caucasus (e.g., Khrami & Loki Massifs - Gamkrelidze et al., 2011; Rolland et al., 2011).

Structurally, the interior of the GC is dominated by south-directed thrusts and reverse faults that progressively steepen toward the interior of the range (Figure 1; Philip et al., 1989; Saintot et al., 2006; Mosar et al., 2010; Adamia et al., 2011b; Somin, 2011; Trexler et al., 2022, 2023). While many prior works describe the structural architecture of the internal GC in the context of a single master structure or structures, often referred to as the Main Caucasus Thrust (e.g., Philip et al., 1989; Mosar et al., 2010), recent work has suggested that the majority of thrusts along the southern margin of the range accommodate similar amounts of displacement (Vasey et al., 2020; Trexler et al., 2022) and especially in the eastern GC it’s actually unclear which structure(s) should be considered the MCT (e.g., Forte et al., 2015b and discussions therein). More critical to our efforts are that many of these structures juxtapose rocks of different composition and/or detrital zircon age populations, so that initiation and activity of these structures during deformation of the GC is expected to have produced diagnostic provenance changes in the foreland basin (Figure 1). Of particular importance is the Vandam zone (Figure 1c), a thrust-bounded terrane of predominantly Mesozoic-aged volcanic and volcaniclastic rocks that is likely a continuation of, or at least genetically linked to, the LC Arc (Kopp and Shcherba, 1985). The Vandam zone was accreted into the range between 13-3 Ma and subsequently deformed (Tye et al., 2022).

2.3 Prior Work on Source Terranes

Potential source terranes and their expected provenance signatures in foreland strata of the Caucasus region are relatively well characterized in terms of U-Pb ages of zircons (Allen et al., 2006; Wang et al., 2011; Cowgill et al., 2016; Vasey et al., 2020; Tye et al., 2020; Forte et al., 2022; Trexler et al., 2022) and to a lesser extent, heavy mineral assemblages (Morton et al., 2003; Morton and Yaxley, 2007; Vezzoli et al., 2014, 2020). Prior work by Tye et al. (2020) integrated both modern sediments and bedrock samples (Allen et al., 2006; Wang et al., 2011; Cowgill et al., 2016; Vasey et al., 2020; Trexler et al., 2022) to define a suite of 7 distinct source terranes distinguishable in detrital zircon U-Pb age populations within the Caucasus region: Eurasian interior, Pre-Jurassic sedimentary rocks, GC basement, GC siliciclastic strata, eastern GC volcaniclastics, western GC volcaniclastics, and Transcaucasus basement and LC arc. While these individual sources do not correspond to single mapped units (Tye et al., 2020), they do define three broad geographic groups: those that reflect a source from the East European Craton to the north of the GC (Eurasian interior), a GC source (Pre-Jurassic sedimentary, GC basement, GC siliciclastic strata, eastern GC volcaniclastics, western GC volcaniclastics), or a LC source (Transcaucasus basement and LC arc). In more detail, the GC sources roughly correspond to distinct tectonostatigraphic and, in part, geographic zones within the GC itself, with the Pre-Jurassic sedimentary and GC basement reflecting exposures in the core of the western orogen, the GC siliciclastics corresponding to the Jurassic to Cretaceous flysch exposed throughout the range, and the western and eastern GC volcaniclastics corresponding to the two volcanic packages along the southern rangefront, the latter of which is also effectively the same as the Vandam zone (Figure 1). The 7 source terranes defined by Tye et al. (2020) largely reflect differences in the relative proportions of 6 different distinct age populations within given samples, specifically: (1) grains < 90 Ma associated with the LC arc, (2) grains 90-200 Ma associated with the LC arc or GC rifting, (3) grains 200-380 Ma associated with the Variscan orogeny, (4) grains 380-500 Ma associated with an earlier arc that formed along, and then rifted from, the former northern margin of Gondwana prior to accretion onto the southern margin of Eurasia (Laurussia), (5) grains 500-900 Ma associated with the Pan-African orogeny, and (6) >900 Ma grains associated with East European craton. Recently, alternative characteristic age divisions within GC and LC detrital zircon ages have been presented by Vasey et al., (2024) that clarify details of the Mesozoic and Paleozoic history of the region, but as the exact interpretations of these age divisions are not critical for our understanding of the recent (i.e., late Cenozoic) structural history of the GC or KFTB, we elect to maintain the somewhat simpler divisions of Tye et al., (2020).

A relatively smaller amount of work in terms of geographic area covered has considered the heavy mineral assemblage of potential source terranes within the Caucasus region (e.g., Morton et al., 2003; Morton and Yaxley, 2007; Vincent et al., 2007; Vezzoli et al., 2014, 2020). Here we focus on results from Morton et al. (2003) and Morton & Yaxley (2007) because Vezzoli et al. (2014, 2020) focus on sources in the far western and northern GC, and so do not appear to be relevant for provenance within the Kura Basin. Morton et al. (2003) and Morton & Yaxley (2007) consider heavy mineral assemblages from the modern Volga (which represents contributions from the East European Craton), the modern Kura River (which drains both the GC and LC), and several smaller rivers draining the eastern tip of the GC. Broadly, the results highlight relatively distinct provenance signatures between all three sources. The Volga is dominated by primarily stable, more evolved and felsic components. In contrast, the Kura River is dominated by more unstable components like clinopyroxene and amphibole sourced from extensive volcanic deposits in the LC. Finally, the GC reflects a mixture of both stable and unstable components, including species like clinopyroxene, but generally in lower abundances than in the Kura River (Morton et al., 2003; Morton and Yaxley, 2007).

2.4 Kura Basin Framework and Regional Timescale

Here we focus primarily on the stratigraphic framework of the Kura Basin, a foreland basin to the southeast of the GC and subbasin of the South Caspian (Figure 1, e.g., Khain, 1975; Philip et al., 1989; Kremenetskiy et al., 1990). Although at present the GC is separated from the Kura Basin by the KFTB and piggy-back Alazani Basin to the north, all three components formed a single continuous basin prior to the formation of the KFTB. Thus, we consider the stratigraphy exposed within the KFTB to largely represent deposition within this former, larger version of the Kura Basin. Results from deep-boreholes drilled during the 1970s reveal that the stratigraphic fill of the central Kura Basin, which spans the Cenozoic, is deposited on top of Jurassic-Cretaceous volcanic rocks thought to be associated with the Lesser Caucasus (LC) arc (Agabekov et al., 1976; Shikalibeily et al., 1988). Seismic velocities within the Kura Basin suggests that the Cenozoic sediment thicknesses exceed 10 km through much of the basin, with thickness likely exceeding 15 km at the western and eastern ends of the KFTB (Gunnels et al., 2020). The seismic velocity of the Mesozoic floor of the Kura Basin is consistent with it either being oceanic crust or highly attenuated continental crust (McKenzie et al., 2019; Gunnels et al., 2020), consistent with it representing a still-subducting portion of the former GC back-arc basin.

Depositional environments represented by strata exposed in the KFTB vary from shallow marine to terrestrial and the strata are predominantly siliciclastic, with general coarsening-upward trends observed throughout most stratigraphic sections (e.g., Agustí et al., 2009; Forte et al., 2013, 2015a; van Baak et al., 2013; Lazarev et al., 2021). Strata exposed in the KFTB were deposited in environments influenced by both the development of the GC and KFTB (e.g., Forte et al., 2013, 2015) and large-magnitude (~1000 m) base level changes of the Caspian Sea during the late Cenozoic (e.g., Popov et al., 2006; Forte and Cowgill, 2013; van Baak et al., 2017; Krijgsman et al., 2019; Lazarev et al., 2021). Variations in Caspian Sea base level, along with potentially related intermittent connections between the Black and Caspian Sea along the southern rangefront of the GC (e.g., Popov et al., 2010; Forte and Cowgill, 2013; van der Boon et al., 2018; van Hinsbergen et al., 2019) are often considered a first-order driver of stratigraphy within the Kura Basin. As such, the stratigraphy of the Kura Basin and surrounding regions is classified in terms of regional stages associated with transgressions and regressions of the Caspian Sea, and associated changes in biota (e.g., Zubakov and Borzenkova, 1990; Jones and Simmons, 1996).

We primarily place our provenance and resulting structural interpretations into the temporal context of the regional Caspian timescale as opposed to a global timescale. We do this for two reasons. First, this approach helps insulate our results from the disruption of future revisions to Caspian timescale and its correlation with the global timescale. Establishing the absolute ages of the boundaries between Caspian stages, their correspondence with stages in the Paratethyan realm more broadly, and their correlation to the global timescale have all proven extremely controversial, with significant revisions and/or shifts numerous times over the past several decades (see review in Krijgsman et al., 2019). Some of these changes were significant enough to shift a regional stage from one global stage to another. While concentrated magneto- and biostratigraphic work has significantly clarified the temporal extents of individual Caspian and related Paratethyan stages, disagreements remain, likely because (1) specific stage-bounding transgressive or regressive surfaces may have formed at different times in different Paratethyan basins and/or (2) the individual stage-bounding surfaces may be time-transgressive within individual basins and their subbasins (e.g., Vasiliev et al., 2011; van Baak et al., 2013, 2017, 2019; Forte et al., 2015a; Richards et al., 2018; Krijgsman et al., 2019; Lazarev et al., 2019, 2021). Because of the long-standing and ongoing problems with correlation of the regional stages to standard international geological epochs, nearly all prior international literature on the stratigraphy of this region has used regional stage names (e.g., Mamedov, 1973; Jones and Simmons, 1996; Vincent et al., 2010, 2013; Vasiliev et al., 2011, 2022; van Baak et al., 2013; Van Baak et al., 2016; van Baak et al., 2017, 2019; Richards et al., 2018; Krijgsman et al., 2019; Lazarev et al., 2019, 2021; Palcu et al., 2019; Aghayeva et al., 2023). Thus, our second reason for using regional stage names is to follow this prior work.

The regional age divisions of primary relevance to the measured stratigraphic sections presented here are, from oldest to youngest: Meotian (base 7.65 Ma - Palcu et al., 2019), Pontian (base 6.12 Ma -Van Baak et al., 2016), Productive Series (base 5.33 Ma - Aghayeva et al., 2023), Ackgahylian (base 2.7 Ma - Krijgsman et al., 2019; base 2.95 Ma - Lazarev et al., 2021), Apsheronian (base 2.1 Ma - Lazarev et al., 2019), and Bakunian (base 0.8 Ma - van Baak et al., 2013) (Figure 2).

In the present study, we use Caspian timescales derived from magnetostratigraphy of several sections in the Apsheron Peninsula and eastern Kura Basin (Krijgsman et al., 2019 and references therein) and the Kvabebi section within the western KFTB (Figure 1; Lazarev et al., 2021). The timescales are equivalent except for the age of the base of the Akchagylian regional stage (Figure 2), which represents a transgressive surface reflecting a ~200 meter base level rise of the Caspian following an extreme (~600 m below modern base level) regression during the preceding Productive Series time (e.g., van Baak et al., 2017, 2019; Lazarev et al., 2021). In the composite timescale of Krijgsman et al., (2019), the Akchagylian spans from 2.7 to 2.1 Ma, whereas in the timescale of Lazarev et al., (2021) the Akchagylian is longer and spans from 2.95 to 2.1 Ma. Lacking a basis on which to choose between these two alternate timescales, we consider both when correlating the KFTB stratigraphy to the global timescale.

2.5 Prior Work on Foreland Provenance

Published studies of provenance in the foreland basins of the GC are limited. Existing results (Figure 1) include isolated data from the Rioni Fold-Thrust Belt and related Cenozoic stratigraphy of the western GC (Vincent et al., 2013, 2014; Tye et al., 2020), the extreme western and eastern termini of the KFTB (Tye et al., 2020), and an expansive dataset focused on exposures of Productive Series strata on the Apsheron Peninsula and in the eastern Kura Basin (Morton et al., 2003; Allen et al., 2006; Morton and Yaxley, 2007; Abdullayev et al., 2018). Those from the KFTB, Kura Basin, and Apsheron Peninsula are the most relevant here.

Results of heavy mineral analysis of Productive Series sandstones sampled on the Apsheron Peninsula are similar to those of the modern Volga River and rivers draining the eastern tip of the GC (Morton et al., 2003; Morton and Yaxley, 2007). This is consistent with the suggestion that during the extreme Caspian Sea low-stand coeval with Productive Series deposition, the paleo-Volga River mouth migrated southwards and entered the Caspian near the modern day position of the Apsheron Peninsula (e.g., Reynolds et al., 1998; Aliyeva, 2005; Kroonenberg et al., 2005; Vincent et al., 2010). Contrastingly, samples of Productive Series sandstones from the eastern margin of the Kura Basin, near the modern Kura River, contain a decidedly different heavy mineral assemblage, more consistent with samples from the modern Kura River taken near its outlet into the Caspian Sea (Morton et al., 2003; Morton and Yaxley, 2007). Generally, both modern Volga River samples and Apsheron Peninsula Productive Series rocks are characterized by more evolved, felsic heavy mineral assemblages when compared with samples from the Kura River or Kura Basin Productive Series rocks (Morton and Yaxley, 2007). In general, Morton et al., (2003) and Morton & Yaxley, (2007) suggest that the presence of distinctive unstable species like clinopyroxene and calcic amphiboles in sediments are strongly suggestive of LC sourcing. However, Trexler et al. (2022) report both of these phases in Jurassic volcanic and volcaniclastic rocks of the western GC in Georgia.

The heavy mineral results from the Apsheron Peninsula exposures of Productive Series sediments are largely reinforced by detrital zircon age populations (Allen et al., 2006; Abdullayev et al., 2018), which are dominated by >900 Ma grains characteristic of the East European Craton and rivers draining this terrane (Safonova et al., 2010; Wang et al., 2011; Tye et al., 2020) and which are encapsulated into the Eurasian Interior DZ source defined by Tye et al., (2020). In contrast, detrital zircon data from the extreme eastern GC and KFTB and western KFTB sampled from sedimentary strata ranging in age from Paleogene to Quaternary record mixtures of source terranes indicative of sourcing from either the GC or LC, with minimal input from the Eurasian Interior (Tye et al., 2020). The majority of foreland samples from Tye et al., (2020) show affinity with one or more of the GC-associated sources, but some samples (e.g., sample CF-1), even those extremely proximal to or within the modern GC (e.g., sample EF-6), show affinity with the Transcaucaus basement and LC arc source. Where such provenance affinities are present, Tye et al., (2020) largely follow Morton et al., (2003) in considering these samples to reflect deposition of sediment delivered by a paleo-Kura river system, predominantly draining the LC, requiring a paleo-Kura river that is in part shifted northward and much closer to the GC rangefront relative to its modern position. Ultimately, with respect to the questions we consider here, the majority of existing detrital zircon data within the southeastern foreland; (1) are derived from strata that are largely pre-tectonic with respect to both rapid exhumation of the GC and possible formation of the KFTB and (2) also lack detailed stratigraphic or structural context (Tye et al., 2020), and as such, interpreting either unroofing patterns from the GC or details of the KFTB are challenging. We address these difficulties directly in this work. We begin by describing the stratigraphic context of the provenance samples we analyze (section 3). Next, we introduce methods and results to establish correlations between the sampled measured sections and the regional timescale (section 4). Finally, we present the methods and results of a diverse suite of provenance techniques (section 5).

3 SAMPLE DESCRIPTION AND CONTEXT

The samples that form the basis for this work mainly represent either A) samples of foreland basin deposits with unknown provenance sampled from five Mio-Pleistocene measured stratigraphic sections exposed within the KFTB or B) samples to characterize potential sources for these foreland-basin deposits. The sample types can be further divided into four groups (Tables 1, 2, and 3). In group A there is (1) volcanic ash from within the five measured stratigraphic sections or adjacent regions to enable stratigraphic correlations, and (2) sandstone with unknown provenance from the same stratigraphic sections. Within group B there are (3) modern stream sediments with catchments in adjacent mountains to characterize potential source areas for the KFTB sandstones, and (4) Mesozoic volcanic and volcaniclastic rocks of the Vandam zone now exposed within the GC to further clarify aspects of potential source areas for the KFTB sandstones. The majority of KFTB sandstone samples of unknown provenance were 2-4 kilograms of medium to coarse-grained sandstone whereas sample volume of ash horizons varied depending on thickness of the particular deposits.

3.1 Stratigraphic Context of KFTB Sandstone and Ash Samples

The five measured sections are at Vashlovani and Sarica (Forte et al., 2015a), Xocashen (van Baak, 2010; Forte, 2012; van Baak et al., 2013), Bozdagh (Forte, 2012), and Goy (Forte et al., 2013; Lazarev et al., 2019) and we refer readers to the source publications for detailed stratigraphic descriptions, logs, and ancillary data such as biostratigraphy (Figure 1, 2). To facilitate placing the 8 ash and 27 sandstone samples that come from these sections into stratigraphic context, we provide brief descriptions of the stratigraphy of each measured section in the supplement (Section S1). Sandstone sample names indicate both the name of the measured section and stratigraphic height above base at which the sample was collected. Thus, sample V-15 is from the Vashlovani section, 15 meters above the section base. Original (field) sample names are reported in Table 2. Summary geologic maps showing the detailed locations and geological context of the sections are provided in the supplement (Figures S1-S5).

To interpret the provenance records from the measured sections, it is necessary to correlate them to each other and the regional timescale. Forte (2012) proposed an initial set of correlations between the five measured sections considered here. However, that correlation lacked detailed tephra glass geochemistry reported below (Section 4) and predated both new magnetostratigraphic work (Lazarev et al., 2019) and significant revisions to the regional timescale (e.g., van Baak et al., 2017; Krijgsman et al., 2019; Lazarev et al., 2021). In section 4 we present an updated correlation based on these new data sources and prior magnetostratigraphy (e.g., van Baak et al., 2013) and mapping (Abdullaev et al., 1957; Ali-Zade, 2005; Forte et al., 2015a).

3.2 Context of Samples of Known Provenance

The 13 samples of modern stream sediment (Figure 1) typically comprised >4 kg of medium- to coarse-grained modern river sand collected from the active channel at locations chosen to characterize particular source terranes within the adjacent mountain ranges. The source areas include the Greater Caucasus Paleozoic core (Enguri), Jurassic-Cretaceous Greater Caucasus Basin sediments (Aragvi, Zaqatala, Kumuk, Kish, and Damiraparan), Dzirula Massif (Kvirila), Achara-Trialet and western Lesser Caucasus (Mtkvari, which is the upstream equivalent of the Kura), and Lesser Caucasus Arc (Tovuz, Shamkir, and Zayam). Where applicable, samples were collected up-stream of major dams (e.g., Enguri). For these samples, we present bulk geochemistry as described in the methods section below. Detrital zircon U-Pb age populations for four of these rivers (Enguri, Kumuk, Mtkvari, and Tovuz) were presented by Cowgill et al., (2016). For the 11 volcaniclastic samples from the Vandam, we analyzed bulk geochemistry for all and sandstone petrography for a subset (6). A detrital zircon population was published for one of these samples (AB0862 = SEGC) by Cowgill et al., (2016).

4. STRATIGRAPHIC CORRELATIONS

The source publications for each of the 5 measured sections provide existing age estimates (see Supplement Section S1, Figure S1-S5). In this section we use major element chemistry of glass shards isolated from ash horizons (Figure S6) (Table 3) to refine stratigraphic correlations between these sections, and thus their ages.

4.1 Analytical Methods for Major Element Geochemistry of Volcanic Glass

Major element fingerprinting of volcanic glass shards within tephra deposits is a useful stratigraphic correlation tool (e.g., Lowe, 2011; Lowe et al., 2017). For this study, geochemical analyses were conducted on volcanic glass shards (125-250 µm) manually separated from 8 tephra samples collected from locations throughout Georgia and Azerbaijan; an additional 9th sample (B-A) from Bozdagh yielded no usable glass shards. Five of the samples came from measured sections described previously (B-B from Bozdagh, X-2A, X-3A, X-3B from Xocashen, and G-A from Goy), whereas the other three (TG, WQ-A, and WQ-B) were collected in similarly aged units in the eastern KFTB mapped by Forte et al., (2013), which we include largely for future work in this region. Sample locations are in Table 3. All tephra samples were separated and cleaned following common tephra preparation procedures (e.g., Roman et al., 2008). Specifically, samples were first wet sieved at Arizona State University (ASU) using 20-40-60-80 mesh sieves. The 40-60 mesh fractions were washed with 5% nitric acid to remove any carbonates, rinsed with deionized (DI) water, and then washed with 5% hydrofluoric acid (HF) one to three times, in 2-minute ultrasonic baths to remove clay adhering to the glass shards. Glass shards were then mounted in epoxy rounds, polished, and carbon coated for analysis in an electron microprobe.

Individual glass shards were analyzed for major element oxide abundances (SiO_2, Al_2O_3, K_2O, Na_2O, CaO, MgO, MnO, Fe_2O_3 and TiO_2) using a JEOL JXA-8530F Electron Probe Microanalyzer (EPM) with JEOL software in the John M. Cowley Center for High Resolution Electron Microscropy at ASU. Using wavelength-dispersive spectrometry (WDS), the instrument was operated at 15 kV, with a 10 nA beam current and a 15 µm defocused beam to minimize alkali loss (Froggatt, 1992; Lowe, 2011). All data were adjusted using atomic number (Z), absorption (A), and fluorescence (F) corrections. If possible, 20 or more glass shards were analyzed for each sample. To assess analytical precision, the Lipari glass INTAV standard (Kuehn et al., 2011) and the Los Posos Rhyolite (RHY5) in-lab standard were run at the start and end of an analysis session, and after every 40-60 unknown analyses.

Major element analytical results are reported as un-normalized data averages with 1σ standard deviation error (Table 3). Brief descriptions of the glass and crystals (if present) are also provided in Table 3. Individual shard analyses are reported in the supplement (Table S1). Individual analyses with totals <90% or with otherwise anomalous values (e.g., SiO_2 > 90%) were not included in the averages or later statistics but are still reported in the supplement. Low totals can be a result of alteration (potential leaching) or analytical issues and are not viable for considering stratigraphic correlations.

4.2 Statistical Methods for Major Element Geochemistry of Volcanic Glass

In our treatment of the major element data for the volcanic glasses, we primarily follow recommendations from Lowe et al., (2017). Specifically, we explore potential correlations with plots of log-ratios of various major elements pairs and select one set (CaO/Al_2O_3 and TiO_2/Fe_2O_3) that provided meaningful separation of different tephra beds or components. Prior to plotting, rounded zeroes (quantities measured but present in amounts below the detection limit) were replaced by nonparametric imputation as described by Martín-Fernánez et al., (2003) using the CoDaPack software package (Comas-Cufí and Thió-Henestrosa, 2011). We compare this with the results of a principal component analysis (PCA), a technique for reducing dimensionality (Krzanowski, 2000), applied to all of the major oxides. Prior to PCA, the oxide concentrations were normalized using a standard scaler so that data were normally distributed with a zero mean and unit variance (Lowe, 2011; Lowe et al., 2017).

We also estimated the similarity of the tephra samples via a modified Euclidean distance measure, D^2, defined by Perkins et al (1995) where,

$$D^2 = \sum_{k=1}^{n} \left[\frac{(x_{k1} - x_{k2})^2}{2\sigma_k^2} \right]$$

and x_{k1} is the concentration of element x_k in the glass of tephra 1, x_{k2} is the concentration of element x_k in the glass of tephra 2, σ_k is the analytical precision of element x_k, and n is the number of elements used in the comparison. We refer to this modified Euclidean distance measure as the "Perkins Distance". Here we select five of the major oxides, CaO, Fe_2O_3, MgO, MnO, and TiO_2, for this distance calculation. We follow Perkins et al., (1995) and do not include Al_2O_3 and SiO_2 in this calculation because they do not show much variation for the majority of samples and could bias the distance measures. Similarly, we exclude Na_2O and K_2O from the calculation because the concentrations of these elements are sensitive to post-depositional hydration of glass shards. Calculated D^2 measures have a chi-squared distribution, and thus with five elements (five degrees of freedom), two tephras can be considered statistically different at the 95% and 99% confidence levels if D^2 exceeds 11.1 and 15.1, respectively. Correspondingly, D^2 less than these critical values suggest that the respective tephras may be correlative. We report the D^2 values in Table 5.

4.3 Ash Correlations

Geochemically, 6 of the 8 analyzed ashes contain exclusively rhyolitic shards (Figure S7). The other 2 samples (B-B and X-3A) both have two compositional groups, with rhyolite shards

(Mode 1) most abundant and a secondary population (Mode 2) that is somewhat geochemically diverse and distinctly lower in silica, having trachyte to trachyandesite compositions (Figure S7). Bi-plots of log ratios and PCA reveal four broad tephra groupings, one of which includes the Mode 2 shards (Figure 3). Key observations from the bi-plots and PCA for correlating the measured sections are: (1) tephras X-3B and X-2A within the two younger Xocashen sections (plus TG at Goy, see below) are similar and likely indicate a single eruptive source, consistent with other stratigraphic correlations based on the Apsheronian-Bakunian boundary in both sections (van Baak, 2010; van Baak et al., 2013) and (2) tephras X-3A in Xocashen, B-B in Bozdagh, and G-A in Goy are similar and likely represent a second eruptive source. Note that the pairs of Mode 1 and Mode 2 shards in X-3A and B-B also appear similar to each other, although the Mode 2 shards have significant scatter (Figure 3, S7). Although Mode 2 shards are absent from the sample of G-A tephra, we did observe in the G-A ash a distinctively more mafic interval that may represent this Mode but that we unfortunately did not sample (Figure S7).

Outside of the measured sections, tephras WQ-A and WQ-B were both sampled from a single outcrop of unit Unit G3 in the Goy area (Forte et al., 2013), with WQ-A stratigraphically below WQ-B by ~40 cm. These two samples group with each other but are distinct from all other samples analyzed here, indicating they likely represent tephras from a third, distinct eruptive source. Tephra TG was collected from a thrust-bounded slice of Unit 2G in the Goy area and was assumed by Forte et al., (2013) to correlate with tephra G-A in the Goy section. However, the new geochemical data indicate TG correlates with tephra X-3B and X-2A in Xocashen, not with G-A.

For all the tephras, the correlations derived from the bi-plots are largely identical to those interpreted from statistical distance (Table 5). In detail, the statistical distance measure does not suggest that the more mafic mode 2 of tephras X-3A and B-B are correlative, but this likely reflects the relatively large variability in the geochemistry and small number of shards analyses, with only one shard from X-3A classified as Mode 2.

4.4 Correlations

The new ash geochemistry establishes new ties between Xocashen, Bozdagh, and the Goy sections. Additionally, magnetostratigraphy in Xocashen (van Baak et al., 2013) and Goy (Lazarev et al., 2019) strengthen the correlations between these two sections. Combining these data with prior age calls from geologic mapping (Abdullaev et al., 1957; Ali-Zade, 2005; Forte, 2012) and biostratigraphy (Forte et al., 2013, 2015a; van Baak et al., 2013; Lazarev et al., 2019) allows us to correlate the different sections both to each other and the regional timescale (Figure 2). A summary of the key datasets informing our correlations are: (1) magneto- and biostratigraphy allow for direct correlation between Xocashen and Goy and both the regional timescale and global paleomagnetic timescale (van Baak, 2010; van Baak et al., 2013; Lazarev et al., 2019), (2) new ash geochemistry allow for direct correlation between portions of the Xocashen, Bozdagh, and Goy sections (Figure 3), (3) maximum depositional ages from U-Pb ages of detrital zircons in Sarica and Vashlovani allow connection between the global absolute timescale and the regional timescale (Forte et al., 2015a), and (4) mixtures of biostratigraphy, lithostratigraphy, depositional environment interpretations derived thereof and inferred relations to Capsian stages, allow for further correlation between stratigraphy in all sections and the regional timescale (e.g., Abdullaev et al., 1957; Ali-Zade, 2005; Forte, 2012; Forte et al., 2013, 2015a; van Baak et al., 2013; Lazarev et al., 2019). Below we consider specific correlations between units within the measured sections and their respective correlations to the Caspian regional timescale.

Based on these data, the Meotian-Pontian stage is exclusively represented by Vashlovani unit V1, which does not correlate to any portions of the other sections. The Productive Series stage is represented by Vashlovani unit V2 and Sarica unit S1. Note that within Sarica, Forte et al., (2015a) previously used a small sub-population of zircons from sample S-210 near the top of unit S1 to determine a maximum depositional age (MDA) of 2.5 ± 0.24 Ma. This MDA is consistent within uncertainty with deposition during Productive Series time if the age of the Productive-Akchagylian boundary is 2.7 Ma (as reported by Krijgsman et al., 2019), but it is inconsistent if the boundary is at 2.95 Ma (as reported by Lazarev et al., 2021). Although resolving this question is beyond the scope of the present work, it does indicate that the exact position of the Productive-Akchagylian boundary in the Sarica section may be unclear. For our purposes, we assume that the entirety of S1 is within the Productive Series to be consistent with Forte et al., (2015a).

The Akchagylian period is represented by the basal portion of unit V3 in Vashlovani, S2 in Sarica, X1 in Xocashen-1, and G1 in Goy, which all correlate to each other based on prior results from Forte et al. (2013, 2015a). Forte et al., (2015a) previously reported a relatively large population of young zircon grains in sample V-1240 from Vashlovani unit V3, which they used to establish an MDA of 2.66 ± 0.046 Ma. At the time of publication of Forte et al., (2015a), the maximum depositional age corresponded to a long hiatus between the Akchagylian and Apsheronian (van Baak et al., 2013), making it unclear if the sample was deposited during the

Akchagylian or Apsheronian. Subsequent work has refined the age of the Akchagylian-Apsheronian boundary to 2.1 Ma (e.g., Krijgsman et al., 2019; Lazarev et al., 2021). Thus, the MDA from V-1240 is now consistent with deposition during either early- or mid-Akchagylian time, depending on which timescale is chosen.

The Aphseronian period is represented by the upper portion of Vashlovani unit V3, Sarica units S3-S5, Xocashen-2 unit X2, Bozdagh units B1-B3, and Goy units G2-A, G2-B, G2-C, and G3, as well as one tephra horizon represented by X-3B, X-2A, and TG and another represented by X-3A, B-B, and G-A. Our interpretation of V3 follows prior mapping from Abdullaev et al., (1957), which places the upper portion of this unit within the Apsheronian. However, V3 lacks a clear lithostratigraphic break, so the location of the Akchagylian-Apsheronian boundary within this unit is uncertain. At first, the correlation between Xocashen ash X-3A and Goy ash G-A may seem at odds with prior magnetostratigraphic results in these two sections (van Baak et al., 2013; Lazarev et al., 2019), but as described in detail in the supplement (see Supplement Section S1.6) are reconcilable if the different sedimentation rates of these two sections are considered.

The Bakunian period is represented by Xocashen-2 units XB and X3 and is not directly represented in other sections. Because the upper bounds of the Apsheronian in both Sarica and Bozdagh are not well constrained, the upper parts of these sections may be of Bakunian age, but we do not implement such a correlation here as we have no direct evidence.

5. SEDIMENT PROVENANCE

We apply a variety of methods to determine the provenance of samples taken from the measured sections, including sandstone petrography, bulk sediment/rock major and trace element geochemistry, and detrital zircon geochronology (Table 2). We analyze each data type using several different statistical and/or visualization approaches, resulting in a varied and multifaceted study. Ultimately, many of these statistical and/or visualization approaches provide similar conclusions, so for the sake of clarity we present in the main text a streamlined view of the methods, results, and statistical/ visualization approaches, with the additional information provided in the supplement for completeness.

In the following sections we consider each type of provenance data separately, first presenting the relevant analytical methods, then the statistical treatments/visualizations we apply to the data, and finally the results and our interpretations. For the geochemistry and petrography data we define new provenance sources here. In contrast, for the detrital zircon geochronology data we use source characterizations previously defined by Tye et al. (2020). Importantly, the two different sets of provenance sources are not the same because of differences in sensitivity between the methods. As we elaborate in the discussion, exploring these differences in sensitivity explains why the different methods appear to record different apparent histories and sources and allows us to leverage those differences to gain deeper insight into the evolution of the KFTB.

5.1 Sandstone Major and Trace Element Geochemistry and Petrography

Both sandstone petrography (e.g., Dickinson, 1970; Dickinson and Suczek, 1979; Ingersoll et al., 1984; Ingersoll, 1990) and major and trace element geochemistry (e.g., Bonjour and Dabard, 1991; Totten et al., 2000; Von Eynatten, 2003; Von Eynatten et al., 2003) are well established methods for determining sediment provenance. It has been suggested that major and trace element geochemistry of bulk-sediments provides a means of discerning provenance that is less biased by effects of chemical alteration and weathering than traditional petrographic approaches (e.g., Dickinson, 1970) and effects of hydraulic sorting that may influence heavy mineral data and related geochronologic techniques (e.g., Von Eynatten et al., 2003; Pe-Piper et al., 2008). However, as applied to the Kura Basin sandstones, the results and implications of bulk geochemistry and sandstone petrography are effectively the same (see Section 5.1.6). As such, we focus here on the use of trace elements to characterize provenance, reporting the methods, results, and discussion of our sandstone petrography in the supplement (Section S2.1, Figures S8 and S9).

5.1.1 Analytical Methods for Major and Trace Element Analysis

We obtain major and trace element geochemical analyses for 26 of the total 27 sandstone samples from the KFTB (unknown provenance), 13 samples of modern river sediment (known provenance), and 11 samples of Mesozoic Vandam volcaniclastic rocks (known provenance), complete results for which are in Table S4. For all but one sample (G-200), these were the same sample material analyzed for sandstone petrography (see Section S2.1). We obtained interior sections of each sample by removing weathering rinds and then sent ~200 grams of each sample to Activation Laboratories Ltd. where they were crushed and analyzed according to their Code 4Lithoresearch and Code 4B1 protocols, which are similar to those used by Pe-Piper et al. (2008) and yield concentrations for 44 different elements in total (Table S4). In particular, major-and trace element concentrations were measured using lithium metaborate/tetroborate fusion ICP analysis and ICP-MS analysis, respectively.

5.1.2 Statistical Methods for Major and Trace Element Analysis

Numerous methodologies have been developed to use the bulk rock major and/or trace element geochemistry analyses of siliciclastic sediments to establish tectonic setting (e.g., Bhatia, 1983; Bhatia and Crook, 1986; Roser and Korsch, 1986; Herron, 1988; Totten et al., 2000), provenance (e.g., Roser and Korsch, 1988; Bonjour and Dabard, 1991; Pe-Piper et al., 2008), or degree of chemical weathering (e.g., Nesbitt and Young, 1982; Harnois, 1988; Fedo et al., 1995). In this work, we consider all three applications of the geochemical data, but in the main text we primarily focus on the use of trace element geochemistry with multivariate statistical techniques to characterize potential source terranes and then classify samples of unknown provenance within that context. In the supplement (Section S2.2) we provide additional methods and results related to both basic tectonic discrimination (Figure S10, S11) and chemical weathering indices (Figure S12) that largely reinforce points that are made clearest with the multivariate statistical treatment.

Importantly, before applying multivariate statistical techniques, it is necessary to transform raw compositional data into a form that does not violate the underlying assumptions of those methods, specifically that input data follows a multivariate normal distribution (Aitchison, 1986; Von Eynatten et al., 2003). Several different transformations have been proposed to convert compositional data into a form more appropriate for use in multivariate statistics, and from these we elect to use an the isometric log-ratio (ILR) because it converts compositional data into values suitable for any standard multivariate statistical approach (e.g., Egozcue et al., 2003; Egozcue and Pawlowsky-Glahn, 2005; Pawlowsky-Glahn and Egozcue, 2006). We provide an expanded discussion of alternate transforms in the supplement (Section S2.2.1).

For the multivariate statistics we test two different suites of elements. The first is a suite of 17 trace elements (Sc, V, Cr, Co, Ni, Rb, Sr, Y, Zr, Nb, La, Gd, Yb, Hf, Ta, Th, U) and one oxide (TiO_2), which is suggested by Pe-Piper et al. (2008) to provide a good discrimination of source geochemistry in detrital samples. The second suite is a set of 10 major elements (SiO_2, Al_2O_3, Fe_2O_3(T), MnO, MgO, CaO, Na_2O, K_2O, TiO_2, and P_2O_5 and excluding LOI, loss on ignition), which is another suite used by Pe-Piper et al. (2008). For both suites, we replace rounded zeroes in the same manner as for the glass geochemistry using the CoDaPack software, which we also use to transform the compositions into isometric log-ratios (ILR) suitable for multivariate analyses (Table S5). Because our main goal is to understand the relations between the samples, rather than the relations between the measured components, the ILR ratio is suitable even though it is not possible to relate the ILR coordinates to specific measured values (e.g., Egozcue et al., 2003). For this reason, we do not report loadings for the various multivariate analyses performed as they do not provide useful information.

To characterize variability and evaluate potential populations within the source terranes, we analyze the ILR transformed compositions for the major and trace element groups of the modern river sediments and Vandam volcaniclastic rocks using both hierarchical clustering analysis and principal component analysis (PCA). These methods have previously been applied to geochemical investigations of provenance data and are useful for understanding potential groupings (e.g., Smosna et al., 1999; Pe-Piper et al., 2008). Hierarchical clustering essentially evaluates the “closeness” of given samples to each other and the results are typically represented graphically on a dendrogram (Krzanowski, 2000). PCA is a technique for reducing dimensionality (Krzanowski, 2000) and can also be evaluated graphically, with similarity being indicated by a grouping on a plot of the principal component (Pe-Piper et al., 2008). We perform both the hierarchical clustering and principal component calculations in the "R" software package (Team, 2010), using the "pvclust" library (Suzuki and Shimodaira, 2009) in the hierarchical clustering analysis to generate a dendrogram with boot-strapped p-values (Shimodaira, 2004) to provide an estimation of the robustness of the clusters indicated on the dendrogram. In detail, we use the "Ward" method of clustering and the "Euclidean" distance. In both the cluster analysis and PCA, the suite of major elements does not prove useful in discriminating different populations and in the case of the principal component analysis fails to capture significant portions of the data variance, so these results are not presented, and the major elements set are not used in future analyses.

We then use the results of the clustering and principal component analyses of using the suite of trace element data to inform choices of groups for linear discriminant analysis to classify the unknown samples from the KFTB. Unlike the PCA or hierarchical clustering analysis, which do not require any a priori assumptions about the relation between samples, linear discriminant analysis is a guided machine learning approach that uses a set of training data divided into known groups to calculate the initial linear discriminant functions (Krzanowski, 2000). These functions are then used to classify unknowns as members of one of these preset groups. We complete these calculations in the "R" software using the "MASS" library (Venables and Ripley, 2002). We use the modern sediments and Vandam volcaniclastic rocks as the training dataset to calculate the linear discriminant functions. We calculate multiple discriminant functions, using the ILR transformed compositions with different group assignments, which are described in more detail in the results section. To assess the robustness of each set of discriminant functions, we perform cross-validation by iteratively recalculating the discriminant functions with one sample from the training data excluded. This sample is then classified according to the calculated discriminant function and the overall percentage of correctly classified training data provides an indication of the robustness of the chosen groups and the accuracy of the functions. Finally, the KFTB samples are classified using the calculated linear discriminant functions.

5.1.3 Multivariate Characterization of Potential Source Areas

Analyses of the ILR-transformed trace-element suite of potential source areas in terms of both PCA (Figure 4a) and hierarchical clustering (Figure 4b) shows that rivers draining the GC (GC, N=7) are generally geochemically distinct from both the 4 rivers draining the Lesser Caucasus (LC, N=4) and the volcanic and volcanoclastic rocks in the Vandam zone (N=11). In contrast, the Lesser Caucasus rivers and the Vandam zone rocks broadly overlap (Figure 4). Thus, on the basis of trace element geochemistry and multivariate statistics we can define two broad end-member sources. The first represents sourcing from the GC Interior and is predominantly representative of the Jurassic-Cretaceous flysch, given the extent of the sampled watersheds (Figure 1). The second represents sourcing from predominantly volcanic and volcaniclastic rocks in either the LC arc or Vandam. Two Transcaucasus rivers plot between these two end-member groups (Figure 4a): the Kvirila, which drains the Dzirula Massif (Figure 1), and the mid-basin Kura River, which incorporates drainages from both the GC and LC, although both show more similarity with the GC Interior group than the LC arc/Vandam. Thus, we consider the Transcaucasus rivers as a third broad group within the context of the PCA results and return to this idea when considering the linear discriminant analysis in Section 5.1.4.

Both the PCA and clustering analysis reveal more subtle divisions within the two broad groups and divide each into two separate sub-populations. For the LC-Vandam group, the cluster analysis yields an identical subdivision into two subgroups as the PCA, for which the first two principal components are able to account for ~70% of the variance (Figure 4a). For the GC Interior group, the subdivision indicated by the cluster analysis (Figure 4b) is present but less distinct in the PCA, with the mid-basin Kura River plotting between the main GC and LC-Vandam groups (Figure 4a) as previously noted. In both PCA and the cluster analysis, Vandam sample AB0863 is found to be an outlier. The subdivisions of the two main groups broadly correspond to Si content with a boundary between the two being ~55 weight percent SiO_2. Thus, we refer to the two sub-populations within each group as “High Si” and “Low Si”. In the GC Interior group the Low Si member generally includes watersheds that drain more volcanic or volcaniclastic components and/or that have significant amounts of carbonate, e.g., the Kish and Aragvi rivers have CaO weight percent of 25% and 18%, respectively. We use these subdivisions in the linear discriminant analysis that is considered in the next section.

It is important to note that while at the gross scale, the two broad geochemically defined sources correspond to geographically distinct sources (i.e., the interior of the GC range vs LC and Vandam), the subdivisions within each group lack a clear correlation with geographic location. Specifically, for the GC affiliated rivers, there is no clear along-strike pattern in terms of the two sub-populations. Likewise, for the LC-Vandam group, bedrock samples that are differentiated into the two distinct groups come from outcrops only a few km from each other.

Thus we interpret these internal divisions to reflect geochemical heterogeneity in the sources, but that this heterogeneity is not cross-correlated with either tectonic or geographic location.

5.1.4 Linear Discriminant Analysis to Classify Unknowns - Methods

We use the four populations identified in the hierarchical clustering and PCA to define initial groups for linear discriminant analyses (LDA) (Tables 8, 9). In detail we run 6 different LDAs (LDA-1 through LDA-6), each of which use a different suite of initial groups as training data. The 3 highest-performing LDAs have correct rates of classification from cross-validation of >80% (Figure 5 and Table 6), similar to the methodology of Von Eynatten et al.,(2003). Here we present results from 2 of these (LDA-1 and LDA-3) because there is no robust statistical or geological reason to favor one over the other. We report the third high-performer (LDA-2) in the supplement (Figure S13, S14) because it classifies the KFTB sandstones essentially the same as LDA-1 and yields linear discriminant values that match LDA-3. We do not report the three low-performing LDAs (LDA-4 to LDA-6) because they have correct classification rates from cross-validation of only 40-70%. However, we note that one of the low-performing LDAs uses geographically defined groups in which all Vandam volcaniclastic rocks define one group and all Lesser Caucasus river sediments define another, thus highlighting that the two geographic regions are not geochemically distinct.

The three high-performing LDAs all use groupings based on the results of the PCA and clustering analysis, with the same groupings for the High and Low Si LC-Vandam groups but different groupings for the GC Interior fields. Outlier Vandam sample AB0863 is excluded from all LDAs (Figure 4). In LDA-1, the GC Interior group is divided as indicated by the cluster analysis into the High and Low Si subgroups, with the mid-basin Kura included in the training data as part of the Low Si group (Figure 5 and Table 6). In LDA-2, all of the GC Interior samples are combined in a single group as indicated by the principal component analysis, with the mid-basin Kura River excluded from the training dataset. LDA-3 is identical to LDA-2 except the mid-basin Kura River is included as a separate group.

5.1.5 Linear Discriminant Analysis to Classify Unknowns - Results

Results from applying LDA-1 and LDA-3 to the sandstone samples of unknown provenance are reported in Figures 5 and 6 and Table 7. The most important observation from the geochemical proxies are clear up-section changes in provenance, generally from a LC-Vandam source to a GC interior source (Figure 6).

In LDA-1, the oldest sample in the Vashlovani section (V-15) groups with LC-Vandam (High Si), with all younger samples classified as being derived exclusively from the GC Interior. In contrast, all samples from the Sarica section are classified as having a predominantly LC-Vandam source, except for the youngest sample (S-1735), which groups with GC Interior (Low Si). In both cases there are no systematic up-section variations between High and Low Si subgroups. Classification of the Xocashen section results in a LC-Vandam source for the lower two samples and a GC Interior source for the upper three samples. Similarly, Bozdagh records a LC-Vandam source for the lower three samples and a GC Interior source for the upper sample. LDA-1 classifies the entire Goy section as being derived from the LC-Vandam source. Of note, Goy is the only section where results from LDA-1 and LDA-2 differ significantly, with LDA-2 assigning the upper three samples to the GC Interior source (Figure S13, S14).

Classifying using LDA-3, which includes the mid-basin Kura River as a separate source, produces similar results as LDA-1 and LDA-2 for some of the sections but dramatically different results for others (Figure 5, 6, Table 7). Vashlovani and Sarica are again classified as dominantly sourced from the GC Interior and LC-Vandam, respectively, although Sarica sample S-360 is classified as similar to the mid-basin Kura River. In contrast, all Bozdagh samples are reclassified as being similar to the mid-basin Kura River. Both Xocashen and Goy are partially reclassified, resulting in alterations between GC Interior and Kura sources, although the lowest sample in Xocashen remains as sourced from LC-Vandam.

5.1.6 Interpretation of Bulk Geochemistry In Context with Petrography

While the bulk geochemistry is useful for both defining potential source areas and classifying the KFTB sandstones within that context, it is somewhat abstract without a mineralogic or petrologic context. To address this, we develop a comparison between the geochemistry and the petrography of the foreland sediments by way of using the results of the LDA presented in Section 5.1.4. In detail, we consider only the values of the first linear discriminant (i.e., the x-axis in Figure 5) for the different LDAs. Because the decision boundaries within the LDAs are nearly vertical, the first linear discriminant (LD1) is relatively effective as a single numeric metric of source affinity. Specifically, we use LD1 of LDA-1 and LDA-2. We use LDA-2 rather than LDA-3 because it is simplest to interpret the results of the petrography in the context of LDA-2, which uses GC Interior, LC-Vandam High Si, and LC-Vandam Low Si source divisions, whereas in LDA-3 the mid-basin Kura river source is effectively a mixture of the GC Interior and LC-Vandam sources (Figure S13). It is possible to make this switch because the LD1 values of LDA-2 and LDA-3 are the same, making them largely interchangeable for this purpose.

To compare the LDA results to the sandstone petrography (Figure 7), we first perform a random forest regression using the percentage of the point count components to predict the value of LD1 for both LDA-1 and LDA-2. Random forest regression is a useful method for assessing the importance of sets of multivariate data in contributing to a single variable, in this case, the value of LD1 (e.g., Grömping, 2009). For each LDA, we use the results of the random forest regression to identify the most important components from the sandstone petrography and assess the extent to which they alone or in aggregate correlate to the LDA.

The random forest regression highlights that the 6 most important petrographic components in LDA-1 are calcium rich plagioclase, pyroxenes & amphiboles, volcanic lithics, total quartz, sedimentary lithics, and miscellaneous "other" (Figure 7a, S8). In detail, the combined percentage of the first three components (calcium rich plagioclase, pyroxene & amphibole, and volcanic lithics) is positively correlated with LD1, whereas the combined percentage of the last three components (quartz, sedimentary lithic, and the generic "other" grains) is negatively correlated with LD1 (Figure 7b, S8). This analysis is consistent with the former three components broadly being associated with a LC-Vandam source and the latter three components associated with a GC Interior source. For LDA-2, the random forest regression is similar, but suggests that the two sources are each predominantly defined by only 2 components: calcium rich plagioclase and pyroxenes & amphibole for LC-Vandam source and quartz and sedimentary lithic components for the GC Interior source (Figure 7c). These components show the same positive and negative linear relationships with LD1 as in LDA-1, but with higher correlation coefficients (Figure 7d).

Two details which are important to highlight in the comparison of the geochemistry and petrography are that broadly; (1) the differentiation of LC-Vandam or GC Interior geochemical sources reflect relative abundances of the petrographic components discussed above as opposed to strict presence or absence of the relevant petrographic components and (2) the petrographic components that are important in defining the two sources differ in their relative chemical stability (e.g., Lasaga et al., 1994 and references therein). Specifically, the petrographic components that are correlated with the LC-Vandam source (e.g., calcium plagioclase, pyroxene) would be expected to weather more quickly than some of the components that define the GC Interior (e.g., quartz). Thus, an apparent up-section change from a LC-Vandam source to a GC Interior source could reflect a true change in sediment provenance from these two broad geographic source regions or could be reflective of increased weathering of a LC-Vandam like source. We consider these two options further in the discussion in light of the results of detrital zircon U-Pb ages presented in the following section.

5.2 U-Pb Detrital Zircon Ages

5.2.1 Analytical Methods

U-Pb geochronology of detrital zircons is a versatile tool widely used for assessing the provenance of siliciclastic sediments (e.g., Fedo et al., 2003; Andersen, 2005; Gehrels, 2012). We perform U-Pb geochronologic analyses of individual detrital zircons from samples of seven Kura Basin sandstones via laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) at the Arizona LaserChron Center. Analytical procedures relevant at the time of analysis (2011) are described by Gehrels et al. (2006) and Gehrels et al. (2008). Approximately 110 grains were dated per sample. Because the potential existed for observing young grains (<10 Ma) in many of the samples, we used a 20 second integration time for all samples. Analyses were excluded from plots and statistical treatments based on unacceptable discordance, precision, or in-run fractionation. For extremely young grains (<10 Ma), discordance was largely ignored in choosing whether to include or exclude particular analyses because the calculated $^{206}Pb/^{207}Pb$ for these grains are subject to extremely low precision due to the low concentrations of ^{207}Pb (Gehrels, 2012). Complete analyses are presented in the supplement (Table S7)

To consider potential sources for the Kura Basin DZ samples, we also define composite source populations based on the classification from Tye et al., (2020) as described in Section 2.3. Specifically, to define a composite source population we combined available published DZ age populations from individual samples into a single, composite sample using the same set of samples as Tye et al., (2020), including those from Allen et al. (2006), Wang et al., (2011), Vincent et al., (2013), Cowgill et al., (2016), Trexler et al., (2022), Vasey et al., (2020), and Tye et al., (2020), but supplemented with additional samples reported by Forte et al., (2022). For the samples from Forte et al., (2022) not classified by Tye et al., (2020), we use multidimensional scaling (Vermeesch, 2013) to assess which source samples, and by proxy which composite source terrane, these newer samples are most similar to. Multidimensional scaling plots suggest that all of the Forte et al., (2022) samples are best classified as part of the GC siliciclastic composite source. Table 4 lists the samples used from these sources and to which source terrain they are assigned. We also follow Tye et al., (2020) in tracking the 6 distinct age populations defined in Tye et al. and discussed in section 2.3 within both the composite sources and basin samples.

5.2.2 Statistical Methods

For visualizing age distributions, we use both probability distribution plots (PDPs) and kernel density estimates (KDEs), because both have distinct advantages and disadvantages (e.g., Saylor and Sundell, 2016). We use the “densityplotter” software (Vermeesch, 2012) to generate both the PDPs and KDEs for the composite sources and our new samples. We use three different methods to compare the U-Pb ages from our new basin samples with those from potential source terranes: multidimensional scaling (MDS) plots (Vermeesch, 2013), Monte-Carlo unmixing models (Sundell and Saylor, 2017), and Bayesian Population Correlation (BPC) (Tye et al., 2019). Ultimately, the three different methods yield largely similar results, so for simplicity, we focus on the results of the BPC as these are the easiest to quantitatively relate to the results of classifying the sediments by their bulk geochemistry. The supplement contains both methodological details and results of the MDS and Monte-Carlo unmixing models (see Section S2.3). In the following we briefly review key aspects of the BPC method, with similar details for the MDS and Monte-Carlo unmixing provided in supplement Section S2.3.1.

BPC relies on constructing probability model ensembles for each sample and then uses these probability model ensembles in pairwise comparisons to calculate a degree of similarity, i.e., the BPC value (Tye et al., 2019). As shown by Tye et al., (2019), BPC is relatively insensitive to differences in sample size between samples being compared, removing the need for subsampling as is required with unmixing techniques (e.g., Sundell and Saylor, 2017). Output BPC values vary from 0 to 1, where a value near 1 implies a high degree of similarity. The BPC calculation also estimates uncertainty on these values.

5.2.3 U-Pb Age Distributions

We present PDPs and KDEs for both the 7 composite DZ sources (Figure 8) and 7 KFTB DZ samples (Figure 9, S15) to enable visual comparison prior to statistical comparison below. It is important to note that the definition of source terranes is different between the U-Pb detrital zircons and the geochemical classifications, a point we return to in the discussion. The vast majority of zircon ages within the thrust belt samples are Mezosoic and Paleozoic, although there are some Cenozic grains in the two Bozdagh samples (B-280 and B-875) and the lower Sarica and upper Vashlovani samples (S-210 and V-1240, respectively). The only samples with sizeable portions of Proterozoic and older grains are the lower Vasholvani sample (V-15) and both those from Bozdagh (Figure 9, S15). Within the context of the 6 distinctive age populations defined by Tye et al., (2020), the vast majority of samples are dominated by mixtures of <90 Ma grains associated with the Lesser Caucasus arc, 90-200 Ma age grains associated with either the Lesser Caucasus arc or GC rifting, or 200-380 Ma grains associated with the Variscan orogeny. For all samples except V-15, older age populations make up less than 25% of the total grains. Both S-210 and V-1240 are notable for containing statistically significant numbers of extremely young grains with mean ages of 2.5 ± 0.24 Ma (n=3) and 2.66 ± 0.046 Ma (n=47), respectively, which Forte et al., (2015a) used to determine maximum depositional ages. The sources of these young grains are unknown, but they overlap in age with silicic volcanism in both the Lesser Caucasus (Karapetian et al., 2001) and GC (Shcherbakov et al., 2022).

5.2.4 Statistical Comparisons of KFTB Sandstones with Sources

We remove the populations of very young grains from samples S-210 and V-1240 prior to conducting the statistical comparisons because these grains most likely reflect contemporaneous, or nearly contemporaneous, regional volcanism at the time of deposition. Because none of the composite sources have age populations of this age, including these grains would effectively mask the provenance signature in the statistical methods we employ. That problem is particularly acute for V-1240, because the young grains constitute nearly 50% of the total population in this sample. We present the results of the BPC comparison (Figure 10) from west to east. Results of the MDS and Monte-Carlo unmixing are presented in the supplement (Figure S16)

In the BPC comparison (Figure 10), the two Vashlovani samples have the highest degree of similarity with the GC siliciclastic source, along with elevated similarity with the eastern GC volcaniclastic, GC basement, and Transcaucasus basement-LC arc sources. In detail, the second highest similarity in V-15 is to the eastern GC volcaniclastic source, whereas in V-1240 it is to Transcaucasus basement-LC arc. Both Sarica samples show only a strong similarity with eastern GC volcaniclastic (>0.9), with the next highest similarity being Transcaucasus basement-LC arc (<0.6). Both Bozdagh samples are very similar to the Transcaucasus basement-LC arc source (>0.9), but also show some similarity with the GC siliciclastic source (>0.7). Finally, the G-200 sample from Goy is very similar to the eastern GC volcaniclastic source (0.98), with the next similar sources being GC siliciclastic and Transcaucasus basement-LC arc (both <0.7).

Taken together, the results of BPC, MDS, and Monte-Carlo unmixing are broadly consistent with each other (Figure 10, S16). All methods indicate a close correspondence between samples from the same section, with samples from the top and bottom of the same section being more generally similar to one another than to samples from different sections, even if those samples are more closely time-equivalent (Figure S15). In addition, the three methods indicate broadly consistent sources for the individual samples, although there are some exceptions. Vashlovani and Bozdagh show both the most complicated sourcing and the largest amount of disagreement between the methods. For Vashlovani, all methods indicate significant contributions from GC siliciclastic and GC basement, but vary in the extent to which they include eastern GC volcaniclastics or Transcaucasus basement and LC arc. All three methods indicate Transcaucasus basement-LC arc as the primary source for Bozdagh, with some minor inputs from other sources, including GC siliciclastic, eastern GC volcaniclastics, and western GC volcaniclastics, although the proportions or importance of these vary between methods. In contrast, in both Sarica and the lower Goy sample, all methods consistently indicate nearly exclusive sourcing from the eastern GC volcaniclastics source (Figure 10, S16).

6. DISCUSSION

6.1 Reconciling Differing Results of Geochemical and Detrital Zircon Provenance Methods

The most fundamental result of this study is that the geochemical/petrographic and DZ-based approaches yield provenance interpretations for the KFTB sandstones that diverge in meaningful ways for several of the measured sections. The geochemical/petrographic proxies indicate clear up-section changes in provenance from a LC-Vandam source to a GC interior source (Figure 6). In contrast, DZ-based methods generally suggest limited up-section change (Figure 9, 10). Thus, if taken in isolation, each method leads to a different interpreted provenance - and potentially tectonic - history for the Kura basin and GC. To reconcile these apparently divergent results, it is necessary to explain why the results from the two methods differ.

Interpreting the apparent divergence in KFTB sandstone provenance is complicated by the fact that the definitions of the source terranes that naturally emerge from each dataset differ from one another. As a result, there is no single set of source terranes that suitably explains the results from both of the different methods. Specifically, Tye et al., (2020) find that 5 statistically distinct sources within the GC emerge from the U-Pb DZ ages (Pre-Jurassic sedimentary, GC basement, GC siliciclastic, eastern GC volcaniclastics, western GC volcaniclastic) and that samples sourced from volcanic/volcaniclastic rocks in the LC (Transcaucasus basement-LC arc source) can be distinguished from those in the GC (eastern and western GC volcaniclastic sources, Figure 8, 10). In contrast to the 5 sources that emerge from the DZ analyses, our sampling of similar regions using bulk geochemistry yields a maximum of 4 statistically distinct sources within the combined GC and LC and also fails to distinguish Jurassic-Cretaceous volcanic/volcaniclastic sources within the GC from those in the LC (Figure 4, S10).

To explore the cause underlying the apparent divergence in provenance from the different methods, we first consider the relationships, commonalties, and differences within the definitions of source terranes between the DZ and geochemical approaches and clarify how these do, or do not, relate to each other. We then consider how the source-definitions map into implications for the sourcing of the KFTB sandstones before providing a parsimonious explanation for the apparent disagreement.

6.1.1 Source Definitions

The primary difference between the the DZ and geochemical approaches is a difference in the degree of geographic specificity, with the DZ approach providing more geographic granularity than the geochemical/petrographic approaches. The DZ data permit identification of sediment sourcing from specific geographic areas within the Caucasus region that are not distinguishable geochemically. For example, the DZ method has the ability to differentiate contributions to a KFTB sandstone from the southeastern GC rangefront to the northeast (i.e., eastern GC volcaniclastic source) vs. the southwestern GC ragefront to the northwest (i.e., western GC volcaniclastic source) vs. from the LC to the south (i.e., Transcaucasus Basement-LC

Arc source) (e.g., Figure 1 - Tye et al., 2020). In contrast, contributions from these regions are indistinguishable from one another geochemically or petrographically, and would all broadly appear as coming from a single composite LC-Vandam source (Figure 4). The apparent homogeneity of the LC-Vandam source in the geochemical data is consistent with prior suggestions of a genetic link between the LC Arc and the volcanic and volcaniclastic rocks within the GC, and specifically the Vandam (e.g., Kopp and Shcherba, 1985). However, in the context of interpreting provenance within the adjoining foreland, this similarity limits the geographic specificity of geochemical and petrographic classifications. Another example is the ability of the DZ method to identify sourcing of a KFTB sandstone from the interior of the western GC, which would be indicated by contributions from either the Pre-Jurassic sedimentary or GC basement sources (e.g., Figure 1 - Tye et al., 2020), whereas sourcing from anywhere in the interior of the range appears in the geochemical or petrographic data as a generic GC Interior source without the capacity for further geographic clarification (i.e., western vs eastern GC, Figure 4). Unfortunately, attempts to extract more geographic information by considering the sub-populations of the geochemical sources, i.e., the High Si and Low Si sub-populations of both the GC Interior and LC-Vandam sources (Figure 4) are not successful.

The non-overlapping source definitions within broad geographic regions (e.g., all of the GC associated DZ sources vs the two geochemical/petrographic GC sources) are mostly simply explained in terms of lithologic heterogeneity and the sensitivity of the different methods to that heterogeneity. For example, the Aragvi, Kish, and Damiraparan Rivers within the GC all contain, or are directly adjacent to, samples classified as being part of the GC siliciclastic DZ source, but span both GC affiliated geochemical sources, with the Aragvi and Kish Rivers being part of the Low Si GC Interior source whereas the Damiraparan River is part of the High Si GC Interior source. Much of these differences likely reflect variable geology within the source catchments, e.g., both the Aragvi and Kish rivers have high CaO (compared to the Damiraparan), suggesting that in this case the divergence in geochemical classifications may in part reflect the presence or absence of significant carbonate, a characteristic that would not be detectable with detrital zircon geochronology. Similar patterns are observed in the Lesser Caucasus and/or Vandam associated sources. At the individual river level, both the Tovuz and Mtkvari River were classified as a part of the Transcaucasus Basement and Lesser Caucasus Arc source on the basis of their U-Pb ages, and while they geochemically are both categorized as a LC-Vandam source, the Mtkvari is contained within the Low Si subpopulation whereas Tovuz is contained within the High Si subpopulation. Similarly, bedrock samples defined geochemically as either of the LC-Vandam sources are contained within watersheds of catchments from which modern sediment U-Pb age populations were used by Tye et al., (2020) to define the eastern GC volcaniclastic source. This includes bedrock sample AB0862, which geochemically is classified here as from the High Si source, but whose DZ population is part of the samples used to define the eastern GC volcaniclastic DZ source (Cowgill et al., 2016; Tye et al., 2020).

Petrography on some of the samples from the Vandam region in the GC does not reveal distinguishing characteristics for interpreting geographic, or other information from the LC-Vandam sub-populations (Figure 4, Tables 4, S2). Both geochemical populations span samples that are texturally volcanic compared to volcanoclastic and the clast counts and/or modal mineralogy do not reveal systematic differences. The only clarifying detail from the sandstone petrography of the Vandam volcaniclastic samples relates to AB0863, which is an outlier in all geochemical classifications. Compared to the other bedrock samples, AB0863 is completely devoid of calcium rich plagioclase and has relatively low amounts of pyroxene or amphibole, instead being dominated by albite and potassium and/or alkali feldspar. This would broadly suggest that the calcium rich plagioclase, pyroxenes, and amphiboles that are largely absent from AB0863 are important in terms of defining both of the LC-Vandam subgroups from a bulk geochemical perspective.

6.1.2 Intercomparison of DZ and Geochemical Methods in KFTB Samples

Given the apparent divergence between provenance trends for the KFTB sandstones from geochemistry (Figure 5, 6) and DZ (Figure 9, 10), it is instructive to consider direct comparisons between these two methods. For this purpose, we develop an approach for sample-to-sample comparison using the linear discriminant analysis of the geochemical data and the Bayesian population correlation of the DZ data (Figure 15), similar to how we compared the bulk geochemistry and petrography results (Section 5.1.5). For the geochemistry-DZ comparison, we compare the first linear discriminant of LDA-1 and LDA-2 directly to the BPC value for the eastern GC volcaniclastics, GC siliciclastic, and Transcaucasus basement and LC arc sources, as these are most diagnostic in the DZ comparison statistics we considered (e.g., Figure 10, S16).

Comparing the LDA results and those from detrital zircon suggests relatively little relationship between the two (Figure 11). Specifically, sample pairs from measured sections that have a large difference in their linear discriminant value (i.e., different provenance source up section) do not necessarily have large differences in their BPC values for relevant sources. Depending on the particular DZ source considered, small trends can be observed, e.g., a positive correlation between eastern GC volcaniclastic BPC and LDA-1 and a negative correlation between GC siliciclastic BPC and LDA-1 for Vashlovani, but the magnitudes of the BPC differences are small compared to differences between sections, e.g., Sarica compared to Vashlovani. This comparison also highlights a similar, and important, result from comparing the geochemical and U-Pb DZ classification of the source terranes, which is that samples can have strongly similar geochemical affinities but have different DZ sources, as is the case for the sample at the top of Sarica (S-1735) and the 2 Vashlovani samples (V-15, V-1240) (Figure 11).

6.1.3 Mechanism for Provenance Method Divergence

While there are important nuances as discussed in the prior sections, broadly the comparisons between the bulk geochemistry and detrital zircon U-Pb geochronology from samples of both known (i.e., source areas) and unknown provenance (i.e., the KFTB sandstones) suggest that the two provenance methods indicate a potentially different history of sourcing for KFTB sandstones. Specifically, in terms of the bulk geochemistry, most of the locations exhibit an up-section shift from a predominantly LC-Vandam source to a more GC Interior dominated source. In contrast, the detrital zircon analyses from the top and bottom of select sections do not as clearly or consistently show significant changes up section (Figure 9, 10, S16). There are several possible explanations for this disagreement, including (1) sediment recycling and selective weathering within the foreland basin; (2) climatically mediated preferential weathering of unstable components; (3) the non-unique source characterizations via different methods described in the previous sections; (4) sensitivity of different provenance methods to different components within the samples; or (5) biasing of detrital zircon signatures by spatial variable erosion, fertility of source terranes, or other filtering processes. The following discusses the first option, which we favor as the primary explanation because the other four options do not fit with the available data, as the supplement explains (Section S3). In exploring the cause of the apparent discrepancy, we largely focus on understanding the variation in the Sarica section, as it is the most extreme.

In detail, our preferred explanation is that the provenance signatures largely reflect an up-section increase in sediment recycling, such that the sediment source transitions from first-cycle (or initially less-recycled) material eroded from the GC to increasing fractions of recycled versions of this same material as the KFTB developed. Of particular importance is that the primary components that appear to define the LC-Vandam sources mineralogically and geochemically, e.g., calcium rich plagioclase, pyroxene, and amphibole (Figure 7, S8), are also species that are expected to weather at rates several orders of magnitude faster than components that define the flysch source, e.g., quartz (e.g., Lasaga et al., 1994 and references therein). The potential importance of chemical weathering of these components is also consistent with prior work in the GC region, where Morton (2003) highlighted the importance of dissolution of clinopyroxene and amphiboles in Productive Series sediments in terms of considering potential sourcing. Thus, in the Sarica section, we envision a scenario where the base of the section was deposited prior to fold-thrust development and was sourced from the GC with a mixture of both GC Interior and LC-Vandam sources, although the DZ-data indicate the LC-Vandam type source likely dominated, which is a point we return to in section 6.2. As portions of the fold-thrust belt north of the Sarica section began to deform they progressively became a source of recycled sediment for the Sarica region. Specifically, early thrusts within the KFTB exposed rocks of a similar provenance to what is seen at the base of Sarica, causing them to be weathered, eroded, and transported prior to deposition at the site of the Sarica section and resulting in the preferential breakdown of the unstable components that are particularly indicative of the volcanic/volcaniclastic source in the geochemical/petrographic data. As a result, fewer of these volcanic/volcaniclastic components are preserved up section, resulting in the up-section shift geochemical signatures that is mirrored in the petrography, e.g., Figure 7, S8). However, the zircon signature from these recycled sediment remains effectively the same as the original source material from the GC. Additionally, growth of KFTB topography to the north of Sarica would likely begin diverting GC sourced rivers, limiting influx of new detrital zircons into the section. This explanation is also broadly consistent with the up-section increases in chemical index of alteration (CIA – see supplement sections S2.2.3 and S2.2.5) values seen in Sarica and the majority of the other sections, although the CIA values do not suggest deep weathering even at their most extreme (Figure 6, S12). Because sandstone petrography and geochemistry data from the Xocashen and Goy sections exhibit similar up-section trends as Sarica, we infer they also record recycling and a transition from a GC source to one that is more locally derived from within the KFTB. However, without comparable DZ data in Xocashen or Goy, this hypothesis is less definitive and highlights a need for future work.

While we argue that sediment recycling is important for interpreting the provenance signature in the majority of our KFTB sections, it may not be dominant in all sections, as indicated by minimal apparent provenance discrepancies between geochemical and DZ methods. In particular, we interpret both the Bozdagh and Vashlovani sections to reflect limited recycling. For Bozdagh, geochemistry, sandstone petrography, and U-Pb detrital zircon populations all combine to indicate a similar history of sourcing and no change in the degree of recycling, consistent with the relatively constant CIA values throughout the section (Figure 6, 9, 10). Likewise, we interpret the Vashlovani section as recording minimal changes in the degree of recycling because in this case the geochemical and DZ-data both indicate a change up-section that reflects a progressively diminishing LC-Vandam source. These observations from Bozdagh and Vashlovani are a major reason why we prefer sediment recycling as the mechanism to explain the apparent discrepancies in provenance data as opposed to a climatically mediated, regional increase in chemical weathering rates (i.e., the second option), because this latter option predicts up-section changes in the Bozdagh and Vashlovani section that we do not observe.

6.2 Implications for Greater Caucasus and Kura Fold-Thrust Belt Tectonics

To provide a framework within which to consider the evolution of sediment provenance in the KFTB, Figure 12 presents a visualization of changes in sourcing through time and space. For this purpose, we consider the spatial distribution of indicators of sediment provenance during individual regional stages between the Meotian and Bakunian, integrating additional DZ samples from Tye et al., (2020) where relevant. For each time period in Figure 12, and for each section that has data for that time period, we show the relevant portion of the LDA classification (bars - Figure 6) and the dominant DZ sources (stars - Figure 10, S16). None of the samples from Tye et al., (2020) appear within the map area of Figure 12, but we show what DZ provenance is indicated for samples either west or east along-strike within the KFTB at relevant time periods. Where appropriate we consider the degree of BPC similarity between KFTB samples from this study and those from prior work (see Supplement Section S2.3.3 and Figure S17). Below, we summarize our preferred interpretation of the implications of the provenance for GC and KFTB tectonics, with a focus on the across-strike traverse of sections from Sarica, Xocashen, and Bozdagh (Figure 12).

6.2.1 Meotian-Pontian (7.65 – 5.33 Ma)

Vashlovani is the only location within our measured sections that includes a record of the Meotian-Pontian. This portion of Vashlovani records a mixed GC Interior and LC-Vandam source, specifically with a DZ signature that reflects a mixture of the eastern GC volcaniclastic, GC siliciclastic, and GC basement. There is some indication of a potential up-section reduction of the LC-Vandam component during Meotian-Pontian time from the petrography and geochemistry. At present, exposures of volcanic or volcaniclastic rock are very limited along the GC rangefront directly north of Vashlovani (Figure 1). Abundant volcanic/volcaniclastic sources during deposition of the Vashlovani base may indicate that exposures of these volcanic/volcaniclastic rocks were larger during Meotian-Pontian time than at present or that concentrations of volcanic/volcaniclastic components were enhanced via either focused erosion of units with similar exposure as today or lateral transport from areas of the GC range front that expose more of these units.

Outside of the sections, at the western (CF-2) and eastern (EF-5) tips of the KFTB, undifferentiated Meotian-Pontian and Pontian sediments, respectively, record a predominantly GC interior source with a GC siliciclastic DZ signature during this time period (Tye et al., 2020). Without a clear sense of where, stratigraphically, CF-2 is located with respect to the Meotian-Pontian samples within Vashlovani, it is difficult to compare the implications of the differences between the sourcing of this sample, but for EF-5, given its Pontian depositional age, suggests a more exclusively GC Interior type source compared to Vashlovani during the same approximate time period. At the western terminus of the KFTB and considering sample CF-1 from the middle Miocene that precedes the Meotian-Pontian, we see a potentially similar up-section change from a more LC-Vandam source (CF-1) to more GC Interior dominated source (CF-2) (Tye et al., 2020). Importantly however, based on BPCs presented by Tye et al., (2020), CF-1 seems more similar to a Lesser Caucasus (Transcaucasus basement and LC arc) derived source than either of the GC volcanic or volcaniclastic DZ sources (i.e., the eastern and western GC volcaniclastics). Tye et al., (2020) suggest that the presence of a Lesser Caucasus affiliated source in CF-1 reflects material that was deposited more distally to the Greater Caucasus, with the present position resulting from subsequent translation toward the GC via north-directed underthrusting of Kura Basin lithosphere beneath the GC. This remains a viable and likely hypothesis. However, given the clear geochemical relationships between the Lesser Caucasus volcanics and volcaniclastics and those exposed at least in the eastern GC (e.g., Figures 4, S8), an alternative hypothesis is that there was sufficient variability in a formerly larger thrust slice of volcanic and volcaniclastic material within the GC rangefront that zircons sourced from this thrust sheet could in part look more like those preserved in the surficial Lesser Caucasus today. While speculative, the general expectation of a shared tectonic history between the Jurassic-Cretaceous volcanic and volcaniclastic rocks exposed in the modern LC and the modern southern GC (Kopp and Shcherba, 1985), opens the possibility that a more complete section of the LC arc-Vandam rocks might contain larger age suites than in the tectonically isolated, and geographically separated, sections we observe today. More detailed stratigraphy in the region around the Gombori Range, specifically paleo-current measurements, could help to differentiate these two mechanisms, i.e., do the strata from which the CF-1 sample comes record dominantly south-directed (GC sourced) or north-directed (LC sourced) paleocurrents? Similarly, a better sense of the volcanic stratigraphy within the Jurassic and Cretaceous Lesser Caucasus could provide an indication of whether there are regions characterized by single-age DZ peaks, similar to the volcanic and volcaniclastic sources within the GC.

Deposition in Vashlovani and elsewhere during the Meotian-Pontian (~7 to 5.5 Ma) is coincident with increases in exhumation rate observed throughout the GC between ~10-5 Ma (e.g., Avdeev and Niemi, 2011; Vincent et al., 2020; Forte et al., 2022; Tye et al., 2022). This similarity of timing is broadly consistent with the idea that the onset of rapid exhumation of the GC prior to the Meotian-Pontian had established the GC as a dominant sediment source for regions within the southern foreland (e.g., Tye et al., 2020).

6.2.2 Productive Series (5.33 – 2.95/2.7 Ma)

Both the Vashlovani and Sarica sections preserve portions of the Productive Series, but they suggest relatively different sourcing at this time (Figure 12b). Vashlovani records a dominantly GC Interior source with some limited LC-Vandam input remaining. In contrast, Sarica is almost exclusively sourced from LC-Vandam with an eastern GC volcanic detrital zircon signature. Present-day catchments north of Sarica within the GC reflect mixtures of the volcanic and flysh bedrock, so the dominance of LC-Vandam input in the Productive Series within Sarica appears to require greater proportions of this source at the time of deposition than is seen today, similar to the lower part of Vashlovani. Again, explanations for this pattern are either a physically larger exposure of the volcanic and volcaniclastic source within the southern range front at the latitude of Sarica, enhanced erosion of this source during Productive Series time, or lateral transport from an area of the GC rangefront with larger exposures of volcanic rocks.

Near the eastern terminus of the KFTB, Productive Series sample EF-6 from Tye et al., (2020) records a mixed affinity with both Lesser (Transcaucasus basement and LC arc) and GC (GC siliciclastic) DZ sources, but here we consider whether EF-6, like its central KFTB counterparts, might instead reflect sourcing from the GC, not the LC. Tye et al., (2020) interprets the Transcaucasus basement and LC arc component to reflect eastward transport of Lesser Caucasus material, either directly from the Lesser Caucasus via an axial drainage or erosion of Kura Basin sediments, most likely related to the coincident draw down of the Caspian Sea (e.g., Popov et al., 2006, 2010; Krijgsman et al., 2010; Forte and Cowgill, 2013; van Baak et al., 2017) and resulting incision by the Kura River (e.g., Kroonenberg et al., 2005). However, at present, both Vashlovani and Sarica are at a greater distance from the GC range front than EF-6 (e.g., Figure 1, 13) and thus it is strange that EF-6 would reflect transport from the Lesser Caucasus or incised Kura Basin sediments while both Vashlovani and Sarica were dominantly sourced from the GC at this same time. Tye et al., (2020) largely follows suggestions from Morton et al., (2003) of a paleo-Kura river almost exclusively sourced from the Lesser Caucasus and that was located relatively near the GC rangefront, but this contradicts evidence of an entrenched Kura paleo-canyon near the modern axis of the basin during Productive Series time (e.g., Kroonenberg et al., 2005). In detail, the interpretation of a LC source for eastern Kura Basin Productive Series sandstones from Morton et al., (2003) relies primarily on the presence of unstable components within the heavy mineral assemblages of these samples, including abundant clinopyroxene, amphibole, and epidote. The similarity between these assemblages and the modern and paleo-Kura River sourced Productive Series sandstones led Morton et al., (2003) to argue that the Productive Series sandstones necessarily must be sourced from the Lesser Caucasus. Morton et al., (2003) do report heavy mineral assemblages from rivers draining the eastern tip of the GC that contain significant proportions of amphibole, epidote, and clinopyroxene, but in lesser amounts than in the modern Kura River, with more stable minerals (e.g., feldspar, quartz) dominating the extreme eastern GC assemblages. Morton et al., (2003) attribute the higher abundance of stable minerals in the GC rivers to the presence of Jurassic and Cretaceous sediments within the catchments and suggest that the presence of the unstable minerals may be due to recycling of Paleo-Kura sourced Productive Series sediments from portions of the river catchments containing these rocks. However, our analysis suggests that the Vandam domain of the southeastern GC proper also may contribute to these heavy mineral assemblages indicative of more mafic, less evolved source terranes, as such, the underlying association of these unstable components necessarily with a LC source, at least on the basis of heavy minerals alone, is questionable.

To fully reconcile the apparently contradictory results of a potential sourcing of central KFTB sandstones during Productive Series time from the southern margin of the GC coincident with eastern KFTB sandstones from the LC would require; (1) palinspastic restoration of the positions of the Sarica, Vashlovani, and EF-6 locations during Productive Series time – in turn requiring estimates of shortening within the respective regions of the GC and KFTB, (2) constraint on the location of the GC rangefront along-strike during Productive Series time, and (3) ideally some independent constraint on the first order drainage-network structure within the foreland basin during Productive Series time beyond the location of the trunk Kura River.

Generally, none of these details are sufficiently constrained to fully resolve this question. However, we again highlight that larger-than-present exposures of a former volcanic/volcaniclastic source in the GC with more zircon age variability than observed today provides an alternative and parsimonious explanation for the provenance records from EF-6.

Focusing on the Sarica and Vashlovani sections, we interpret the dominance of GC provenance and the coarseness of the Productive Series deposits to result from continued rapid exhumation of the GC and progradation of coarse clastic materials into the foreland basin (e.g., Burbank et al., 1988; Allen and Heller, 2012). The depositional character of these deposits also likely reflects the regional context of the coincident Caspian Sea lowstand (e.g., Forte et al., 2015a). The one Productive Series sample from Vashlovani is notable for being largely devoid of lithic grains (Figure S8, S9) and a temporary increase in CIA (Figure 6), both of which are consistent with an increase in reworking or weathering. This could reflect local reworking resultant from deformation and uplift of Kura Basin sediments, i.e., initiation of the KFTB, but given that these changes are short lived and that overlying basal Akchagylian sediments look very similar to underlying upper Meotian-Pontian sediments in Vashlovani (e.g., Figure 6, S8, S9), we favor an explanation related to the unique Caspian low-stand during the Productive Series deposition and potentially increased weathering during this period.

6.2.3 Akchagylian (2.7/2.95 – 2.1 Ma)

The Akchagylian is present in the Vashlovani, Sarica, Xocashen, and Goy sections (Figure 12c). With the exception of Vashlovani, all sections show a strong affinity for the LC-Vandam sources near their base and with Goy specifically showing affinity to an eastern GC volcaniclastic DZ source. In both Sarica and Goy, up-section toward the Apsheronian boundary, there is a slight decrease in this LC-Vandam source as indicated by petrography and geochemistry. This is not seen within Xocashen, but the Akchagylian-Apsheronian boundary is not captured within our sampled stratigraphy there. Similar to other sections, the base of Goy shows a strong affinity with a LC-Vandam source both geochemically (Figure 6, S11) and in terms of detrital zircons (Figures 9, 10, S16), which is at odds with modern geology because the portion of the GC rangefront north of Goy is an embayment largely devoid of volcanic and volcaniclastic material. As noted above, possible explanations for this difference are larger past exposures of the volcanic and volcaniclastic source within the southern range front, enhanced erosion of this source during Akchagylian time, or lateral transport from an area of the GC rangefront with larger exposures of volcanic rocks.

In Sarica, a marked decrease in LC-Vandam components that is especially noticeable in the sandstone petrography (Figure S8) but also detected geochemically (Figures 6, S11) could reflect either (1) a decrease in the contribution of volcanic and volcaniclastic inputs reflecting a decrease in the importance of this source within the GC at the longitude of Sarica or (2) the beginning of sediment recycling reflective of initiation of KFTB structures north of Sarica and reduction in the volcanic and volcaniclastic component through weathering of unstable phases as described previously. Presumably, detrital zircon ages from this horizon would help to constrain these options, i.e., if the DZ signature remained dominated by eastern GC volcaniclastic zircons this would suggest sediment recycling, whereas if the DZ signature began to reflect more GC siliciclastic or other non-volcanic GC inputs, this would support a decreasing extent of an eastern GC volcaniclastic source along the southern range front. In the absence of such data, we instead consider the regional tectonic context of the KFTB to help narrow the options. Farther west within the KFTB, the Akchagylian may reflect the initiation of deformation (e.g., Sukhishvili et al., 2021), but the potential time range also includes much of the Apsheronian (e.g., Figure 2). Similarly, Vashlovani during the Akchagylian, which is in a somewhat similar structural position within the KFTB as Sarica, seems to still record sourcing from the GC as opposed to more local KFTB, i.e., recycled GC, sources. This is exemplified by the geochemistry (Figures 6, S11) and detrital zircon (Figure 9, 10, S16) sample(s) during the Akchagylian reflecting a consistent change up-section to a reduced LC-Vandam input, and sandstone petrography that still suggest LC-Vandam clastic inputs (Figure 4). Thus, for Sarica, we favor an explanation for provenance during the Akchagylian as still recording sourcing primarily from the GC. This would imply that the timing of KFTB initiation at the longitude of Sarica likely occurs after the Akchagylian and that the change in provenance from the Productive Series to Akchagylian, reflects a reduction in flux of the LC-Vandam source area from the GC.

6.2.4 Apsheronian (2.1 – 0.8 Ma) and Bakunian

The Apsheronian is represented in all measured sections (Figure 12e), though the extent of its exposure in Vashlovani is uncertain considering the unclear boundary between the Akchagylian and Apsheronian in this location (Figure 2). Through the duration of the Apsheronian, geochemistry and sandstone petrography suggest that Sarica, Xocashen, and Bozdagh all show decreases in LC-Vandam components. This is also broadly coincident with an up-section coarsening in all three columns. However, in Xocashen much of that coarsening occurs after the Apsheronian, during the Bakunian period, and the coarsening in Bozdagh is not as pronounced as in the other two sections. For both Sarica and Xocashen, we interpret these up-section changes in the stratigraphic character as most likely reflecting initiation of the KFTB. For Sarica, this would suggest that structures north of the section location likely began to exhume sometime during the early Apsheronian (Unit S3) or possibly across the Akchagylian-Apsheronian boundary, similar to the timing of initiation of deformation in the Goy region (Forte et al., 2013; Lazarev et al., 2019). For Xocashen, coarsening and reduction in the LC-Vandam associated component occurred later in the Apsheronian and/or into the Bakunian compared to Sarica. This later timing in Xocashen could reflect either a delay related to coarse clastic progradation or that the Sarica fold itself, which is the structure directly north of and across the Adjinour playa from Xocashen, initiated and began to exhume, providing material for southern regions. In the latter case, this would suggest in-sequence propagation, from the structure north of Sarica during the early Apsheronian followed by Sarica during the later Apsheronian and into the Bakunian (Figure 13).

It is worth noting that the degree of synchronicity of significant up-section coarsening and the reduction in the LC-Vandam component vary between Xocashen and Sarica. The two events roughly correspond in Xocashen, i.e. across the Unit X2-X3 / Apsheronain-Bakunian boundary, whereas in Sarica the coarsening starts across the Unit S3-S4 boundary (roughly early to middle Apsheronian) whereas the reduction in the LC-Vandam component occurs closer to the Unit S4-S5 boundary (later Apsheronian). For Sarica, it is unclear if the up-section coarsening or the LC-Vandam reduction better times the initiation of structures within the KFTB to the north. We favor up-section coarsening as being most diagnostic of thrust belt initiation because we assume that the onset of significant weathering is likely to temporally lag behind the transition to coarse sediment arrival from the uplift of structures to the north, in which case the KFTB initiated at this latitude around the Akchagylian-Apsheronian boundary (~2.1 Ma). However, if the reduction in LC-Vandam more precisely dates initiation, then onset here is closer to ~1 Ma. Ultimately, distinguishing between these options likely requires additional detrital zircon geochronology within Sarica, additional stratigraphic observations of areas within the KFTB north of Sarica, and more precise chronologies of all strata.

While Bozdagh shows a reduction in LC-Vandam source components and a slight coarsening upwards, the interpretation of a relatively constant deltaic environment with Transcaucasus basement and LC arc DZ signatures at both the top and bottom of the section do not further constrain KFTB initiation. Instead, we interpret the facies and provenance data to indicate that the Bozdagh section was likely sourced by an east-flowing, longitudinal river that drains both the GC and LC analogous to the modern Kura or other present day axial rivers (Figure 12). Thus, we interpret the reduction up-section of the LC-Vandam component at Bozdagh as likely reflecting an overall reduction in the exposed area of volcanic and volcaniclastic sources in the GC. From paleocurrent data at the western terminus of the KFTB, we know that the development of the KFTB during the Akchagylian-Apsheronian period significantly perturbed the foreland drainage network, as formerly south-flowing rivers were locally defeated and reversed to drain northwards into the piggy-back Alazani basin (Sukhishvili et al., 2021). Thus, if Bozdagh represents a paleo-Kura like drainage, then the up-section changes in provenance in the Bozdagh section could also reflect progressive sequestering in the

KFTB and nascent Alazani basin of material derived from the southeastern GC during the Apsheronian.

Finally, in Goy, the angular unconformity between Akcaghylian and Apsheronian sediments is thought to date the timing of initiation in the KFTB at this longitude (Forte et al., 2013; Lazarev et al., 2019). By the base of the Apsheronian, the provenance of Goy appears to be dominated by GC Interior sources, though coupled with the coarsening upward seen from unit G2-A to G2-B and unit G3 in Lazarev et al., (2019), the independent constraint on the KFTB having initiated by that time suggests the up-section change in the apparent sourcing from geochemistry could also be a recycling signature. Detrital zircon data from higher in the Goy section would likely clarify whether this is the case.

6.2.5 Summary of Tectonic Implications from Provenance

In Figure 13 we summarize our preferred sequence of events within the central KFTB at the longitude of the Sarica, Xocashen, and Bozdagh sections and based on our new provenance data and prior work. During Productive Series time, the southern rangefront of the eastern GC exposed a mixture of thrust-bounded sections of volcanic and volcaniclastic rocks that likely reflect slices of distal LC arc material, overlain by, and in thrust contact with GC flysch (Figure 13a). We hypothesize that at this time, the range-front fault thrusting Mesozoic volcanic rocks over Cenozoic basin fill was the primary active structure in the range, prior to the development of the KFTB. We further infer that the cross-strike width of volcanic and volcaniclastic rocks along the southeastern rangefront of the GC was wider at this time than it is today. This model does not preclude other structures from being active at the time and our data do not directly constraint the history of any of the individual structures within the GC, but the localization of deformation near the rangefront is consistent with in-sequence propagation of structures and the subsequent evolution of the system as we interpret below from the provenance data.

By the time of the Akchagylian-Apsheronian boundary (Figure 13b), exposure of the volcanic and volcaniclastic rocks had progressively decreased as the thrust slice(s) that contained these rocks were exhumed and eroded via south-directed thrusting along the rangefront fault system(s). On the basis of the provenance and stratigraphy, it is at this time, i.e., ~2.1 Ma, that we suggest deformation began to propagate into the foreland, initiating the KFTB and formation of the Alazani piggyback basin (Figure 13b). However, as discussed in Section 6.2.4, we acknowledge that available data do not precisely constrain the timing of initiation of the central KFTB and that onset could be younger and closer to ~1 Ma. We favor the interpretation of an initiation age closer to ~2 Ma because we generally assume that coarse sediment arrival from the uplift of structures to the north of Sarica would precede significant weathering and associated reduction of the LC-Vandam component of this material. However, clarifying the timing within the central KFTB should be a priority in future work. Our preferred interpretation of an ~2.1 Ma initiation for the central KFTB implies broadly synchronous timing for KFTB initiation along strike, with Akchagylian to basal Apsheronian initiation at the longitude of Sarica, Xocashen, and Bozdagh matching KFTB initiation estimated both to the west (Sukhishvili et al., 2021) and east (Forte et al., 2013; Lazarev et al., 2019). Synchronous initiation along strike is contrary to previous suggestions of east-younging diachronous initiation that was inferred from sparse data (e.g., Forte et al., 2010). Based on recent comparisons of low-temperature thermochronology and ^{10}Be exhumation rates (Forte et al., 2022), Akchagylian to basal Apsheronian initiation of the KFTB would be coincident with a larger structural reorganization within the range that caused deformation within the interior of the GC to expand to the north, possibly related to duplexing at depth along the basal GC thrust system (Forte et al., 2015b). In addition, initiation of the KFTB likely resulted in initial slowing of activity on the rangefront fault system and the onset of increasing embayment of the rangefront via erosion and burial as the Alazani piggyback basin began to fill (e.g., Forte et al., 2010; Mosar et al., 2010).

By the time of the boundary between the Apsheronian and Bakunian stages (Figure 13c), we infer that the Sarica fold itself likely began to form, shedding coarser-grained and further-recycled material southward to be deposited at Xocashen (Figure 13c). Such timing implies in-sequence propagation of the KFTB at this longitude, which contrasts with the out-of-sequence propagation seen in portions of the eastern terminus of the belt (Forte et al., 2013) and GC (Tye et al., 2022). Throughout the depositional history, we suggest that Bozdagh experienced deposition from a paleo-Kura-like axial drainage. This axial drainage subsequently entrenched between the Bozdagh and Xocashen folds sometime during the Bakunian stage or later, when both the Xocashen and Bozdagh folds began to form, but our data do not constrain the timing of either of these structures more precisely than initiation during or after Bakunian time.

Ultimately, our preferred sequence of events within the KFTB is consistent with recent work suggestive of more synchronous initiation of the KFTB along strike (Forte et al., 2013; Lazarev et al., 2019; Sukhishvili et al., 2021) and thus is consistent, at least in a structural sense, with widening of the orogen in response to a regional shift to more arid conditions (Whipple and Meade, 2004, 2006; Forte et al., 2013). However, it remains unclear if a climatically induced widening also explains the potentially coincident internal structural reorganization and northward shift of the locus of exhumation within the GC (Figure 13; e.g., Forte et al., 2015b, 2022). Internal deformation within the orogen coincident with widening is not an unexpected response to either changes in taper angle (e.g., Whipple and Meade, 2004, 2006; Hoth et al., 2006) or as part of accretion cycles (e.g., Hoth et al., 2007), but establishing the coincidence of KFTB initiation and internal GC reorganization requires better timing of both, especially the internal reorganization. Remaining uncertainty in the exact timing of initiation of the central KFTB structures along the traverse between Sarica and Bozdagh could be reduced via infilling the detrital zircon geochronology record.

Our results highlight that multiproxy sediment provenance work, paired with additional stratigraphic and structural characterization of regions within the KFTB, may be a viable method for constraining the timing of initiation throughout the thrust belt. Such additional timing information is important for clarifying the drivers of fold-thrust belt initiation and deformation front expansion within the GC. In contrast, tying the structural changes to a potential climatic trigger for initiation requires more paleoclimatic context for the KFTB sediments.

6.3 Implications for Provenance Studies in Forelands

More broadly, results of our work provide some general insights for sediment provenance investigations within other foreland fold-thrust belts. Detrital zircon U-Pb geochronology is unquestionably a go-to method for sediment provenance investigations across a range of tectonic settings (e.g., Gehrels, 2014; Žák et al., 2020; Jian et al., 2022).

However, this method is not without challenges in terms of uniquely interpreting the provenance history while accounting for sources of bias or other complications (e.g., Cawood et al., 2003; Amidon et al., 2005; Andersen, 2005; Link et al., 2005; Lawrence et al., 2011; Raines et al., 2013; Spencer et al., 2018; Malkowski et al., 2019). The results of our analysis echo those of other recent work (e.g., Malkowski et al., 2019), namely that interpretation of detrital zircon geochronology is the most robust when done in concert with other indicators of sediment provenance. In our particular example, the inclusion of bulk rock geochemistry and sandstone petrography is critical for recognizing the potential role of sediment recycling within the KFTB. Furthermore, exploring mechanisms to reconcile the apparent discrepancies between the geochemical/petrographic data and the DZ results leads to insights regarding the timing of onset of sediment recycling and thus initiation of the KFTB, insights that are not apparent from DZ U-Pb populations alone.

One of the reasons for the propagation of DZ as an effectively default provenance method, beyond the ubiquity and durability of zircons in many sediments, is the relative ease and low cost of the analyses (e.g., Gehrels, 2012). In this respect, we emphasize that bulk rock geochemistry of either the same sandstone samples used for DZ geochronology, as we present here, and/or interbedded mudstones (e.g., Pe-Piper et al., 2008; Malkowski et al., 2019) represents a similarly easy and cost-effective provenance technique that pairs well with DZ geochronology. Simultaneous application of both techniques has the potential to reveal additional details regarding the provenance and interpreted tectonic history of a region, as our study demonstrates.

7. CONCLUSIONS

The results of our multiproxy provenance analysis of Kura Fold-Thrust Belt sandstones and potential source regions within the Greater and Lesser Caucasus provide additional context and considerations for future provenance work within the Kura Basin or Fold-Thrust Belt. In addition, these data help to clarify the structural evolution of both the southeastern Greater Caucasus and Kura-Fold-Thrust Belt, and specifically add weight to the suggestion from some prior work that initiation of the Kura Fold-Thrust Belt may have been nearly synchronous along-strike. Specific notable conclusions from this work include:

1. Source characterization, and thus resulting indications of sediment provenance within the foreland, from sandstone petrography, bulk major and trace element geochemistry, and detrital zircon geochronology broadly overlap, but have some important differences. Source terranes defined on the basis of geochemistry or framework grains span geographically broader regions than those defined by detrital zircon populations. Specifically, while prior work characterizing detrital zircon source terranes identifies 7 distinct sources within the Caucasus region (of which 5 represent source from the Greater Caucasus, 1 represents a source from the Lesser Caucasus and Transcaucasus, and 1 represents a source from the Eastern European Craton), we are able to differentiate 2 main sources using sediment geochemistry, one that reflects sourcing from the GC interior (e.g., the basement and/or Jurassic-Cretacous flysch) and another that reflects sourcing either from the Jurassic-Cretacoues volcanic and volcaniclastics along the southern margin of the GC or the similarly aged LC arc rocks. Both geochemical sources can be further refined into two

subpopulations broadly reflective of their relative SiO_2 content, which convey information on the nuanced geology of the particular samples but are not geographically distinct.

2. Within the Kura Fold-Thrust Belt sandstone samples, sandstone petrography and trace element geochemistry are broadly correlative and provide similar information with respect to potential provenance histories. This suggests that with respect to these two methods, future provenance work in the Kura Fold-Thrust Belt could largely focus on inclusion of bulk trace element geochemistry, which is a substantially less work intensive methodology than sandstone petrography.
3. Our geochemical and petrographic data indicate that the majority of Kura Fold-Thrust Belt sections record an up-section change in apparent provenance from a more volcanic and volcaniclastic source (i.e., the LC-Vandam) to one more reflective of sourcing from the interior of the modern GC, which is dominated by Jurassic-Cretaceous flysch. In contrast, U-Pb ages from detrital zircons suggest relatively minimal changes between the bottom and top of the sections, and instead reveal different sourcing between the sections. We interpret that this apparent divergence between the provenance methods in part reflects an up-section increase in sediment recycling and local reworking related to initiation of structures within the belt. This implies that in part, the apparent up-section change evident in the geochemistry and petrography to a modern GC Interior like source is not real, but instead reflects that after weathering of unstable components of the LC-Vandam like source, sediments geochemically/petographically will appear somewhat similar to

the GC Interior source. In detail, while the onset of sediment recycling is captured by the geochemical and petrographic data, the DZ data are insensitive to this change.

4. Integrating provenance changes from the different methods suggests that before the Akchagylian-Apsheronian boundary (~2.1 Ma), a progressive up-section reduction in the volcanic and volcaniclastic component observed within the Kura Fold-Thrust Belt reflects a progressive decrease in the spatial extent of this source in southeastern Greater Caucasus. We interpret this decrease over time to reflect progressive exhumation and erosion of a thrust-bounded slice(s) of the Vandam and equivalent rocks along the rangefront fault system, although other mechanisms are permitted, such as changes in the spatial distribution of focused erosion or along-strike sourcing of sediment.
5. Shortly after the Akchagylian-Apsheronian boundary, we interpret the diminishing volcanic and volcaniclastic component to reflect the onset of Kura Fold-Thrust Belt deformation within the central part of the belt, where the mafic to intermediate, unstable components diagnostic of the volcanic and volcaniclastic source terranes were selectively weathered during recycling and local reworking. This implies that the initiation age of the central Kura Fold-Thrust Belt overlaps with timing constrained in the western and eastern termini of the belt and further indicates that the belt initiated nearly synchronously along-strike. Synchronous initiation of the KFTB is consistent with the proposition that growth of the thrust belt represents a nearly synchronous, major structural reorganization and resultant widening of the GC orogen. Although this reorganization and widening could have been climatically

driven, further tests of that hypothesis would benefit from both more complete regional paleoclimate records and refined timing of initiation of the belt, especially in the western section, near the Gombori Range.

6. The structural history we interpret from sediment provenance implies broadly in-sequence, north-to-south propagation of the locus of active deformation from the southeastern margin of the Greater Caucasus into the Kura Fold-Thrust Belt. Similarly, our results imply predominantly in-sequence propagation of structures within the central Kura Fold-Thrust Belt as well. This differs from histories of out-of-sequence deformation in the eastern Kura Fold-Thrust Belt and eastern tip of the Greater Caucasus, highlighting diverse structural histories over relatively modest (~100 km) distances along-strike.
7. Finally, the results from the Kura Fold-Thrust Belt highlight the utility of integrating diverse sediment provenance methods within actively deforming regions as this may allow both for better characterization of potential biases and complications that could otherwise hinder correct interpretation, but also have the potential to expand the ability to recognize important drivers of provenance change.

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FIGURE CAPTIONS

Figure 1 – Tectonic context, sample locations, and regional geology. a) Locations of major thrusts from Trexler et al., (2022), colored by the ages of strata they structurally juxtapose. Bottom inset shows the maximum, minimum, and mean topography within the A-A’ swath profile (gray) and estimated N25E convergence rates between the Greater and Lesser Caucasus (red) as modified from Forte et al., (2022), which provides further discussion of these plots. Dashed box outlines the extent of the lower two panels. b) Map showing locations of the

modern river and bedrock samples, as explained in the bottom-right legend. Also shown are the locations of samples and their respective detrital zircon U-Pb source terranes from Tye et al., (2020) and references therein plus additional samples from Forte et al., (2022), as explained in the top-right legend. Black lines indicate watershed boundaries for modern sediment samples; bold watershed boundaries indicate catchments for which we present geochemical data and that Cowgill et al., (2016) presented detrital zircon geochronology. Note that modern river samples for Kura and Mtkvari represent samples from the same river, where the Mtkvari is sampled upstream from the Kura and reflects the Georgian (Mtkvari) and Azerbaijani (Kura) names for the river. Gray circles are other foreland provenance samples from Tye et al. (2020), Allen et al., (2006), and Abdullayev et al., (2018), including several suites from the Aphseron Peninsula (AP). Previous foreland samples from Tye et al. (2020) that we discuss in detail are labeled with their sample names (CF-#, EF-#). c) Same as panel b, but over a map showing a simplified version of the bedrock geology from Forte et al., (2014). Also highlighted is the zone of predominantly Cretaceous volcanic and volcaniclastic rocks in the eastern GC, which we refer to here as the Vandam zone, consistent with prior literature (e.g., Tye et al., 2022).

Figure 2 - Stratigraphic correlations of the measured sections based on ash geochemistry (red lines), published magnetostratigraphy (van Baak et al., 2013; Lazarev et al., 2019) (gray lines), and previous mapping (Abdullaev et al., 1957; Ali-Zade, 2005; Forte, 2012; Forte et al., 2015a) (black lines). Colored symbols with numbers to the right of each column indicate samples analyzed here. Boxes containing unit names within each section are colored by depositional environment, as indicated in legend. Black lines show our correlations between the sections,

the global geomagnetic polarity timescale (GPTS - Ogg, 2020), and the regional timescales of Krijgsman et al. (2019) and Lazarev et al. (2021), which differ in Akchagylian duration. In Vashlovani and Goy sections the diagonal boundaries between Akchagylian and Apsheronian indicate uncertainty in the exact location of the boundary within the measured section. Inset map shows locations of stratigraphic sections (black dots) and areas (boxes with red gradients) where timing of the Kura Fold-Thrust belt initiation is constrained to the east (Forte et al., 2013; Lazarev et al., 2019) and west (Sukhishvili et al., 2021). Vertical bars with red shading on the timeline indicate initiation ages of major structures in the region (E = Eastern KFTB).

Figure 3 - Plots of tephra shard geochemistry. Samples from measured sections are indicated in the explanation and indicated at the stratigraphic positions shown on Figure 2. The three ashes marked “Other” come from outside the measured sections and are included for potential future work in this region and are not directly relevant to the main points of this effort. a) Plot of natural log of element ratios highlighting separation of different ash populations and emphasizing the existence of two modes (M1, M2) within ashes X-3A and B-B. b) Plot of principal component analysis of ash shard geochemistry suggesting similar groupings as the log ratios. Notice a significant break in the x-axis, reflecting the extreme difference between all other samples and the M2 shards in samples B-B and X-3A.

Figure 4 - Source area characterization from multivariable statistics of bulk-rock trace element analyses. a) Result of principal component analysis (PCA) highlighting separation of potential source terranes into four semi-distinct zones with one outlier (AB0863); the Kura River sample

plots in the middle of these fields, consistent with the expectation that it is a mixture of all 4 potential sources; GC = Greater Caucasus, LC = Lesser Caucasus, TC = Transcaucasus. b) Result of hierarchical clustering analysis highlighting a similar separation as suggested by the PCA in Figure 4a.

Figure 5 - Results of linear discriminant analysis considering two different source definitions (LDA-1 and LDA-3); cross-validation rates are the same for both. Results including LDA-2 provided in Figure S13.

Figure 6 - Results of two different LDAs (LDA-1 and LDA-3) considered as a function of stratigraphic position. Correlations and timescale are identical to that shown in Figure 2. Also shown are the chemical index of alteration (CIA - Nesbitt and Young, 1982). Comparisons of CIA to other weathering indices are shown in Figure S12 and discussed in Supplemental Text S2.2.5. Note that generally we do not have constraint on where within the sections between samples provenance would change, so the location of the changes shown here are schematic. Version of figure considering results of LDA-2 provided in Figure S14.

Figure 7 - Comparison of linear discriminant analyses of bulk geochemistry and sandstone petrography. a) Results of random forest regression that assesses the ability of a given point count category to predict the value of linear discriminant 1 within LDA-1. Green and blue bars indicate components most associated with a LC-Vandam and a GC Interior source, respectively. Black bars indicate components that are less diagnostic for distinguishing between sources. b)

Plots and linear regressions between summed percentages of components related to either LC-Vandam or a GC Interior source as identified in Figure 4a and linear discriminant 1 of LDA-1. c, d) Same as Figure 7a and 7b but considering linear discriminant 1 for LDA-2.

Figure 8 - Composite detrital zircon populations used to define source terranes, following the definitions by Tye et al., (2020). See text for additional discussion of source terranes. Plot was generated using DensityPlotter (Vermeesch, 2012) with KDEs colored and PDEs hollow. KDEs were calculated using an adaptive bandwidth (see Vermeesch, 2012). Colors of KDEs are for reference in subsequent figures. Colored bars across the top shows 6 diagnostic age ranges identified by Tye et al., (2020). Pie charts show the proportions of these diagnostic ages within each composite sample. Both the total number of zircons that define each source (n) and total samples contributing to the source (N) are shown. Composite samples are detailed in Table 4 and reported by Allen et al., (2006), Wang et al., (2011), Cowgill et al., (2016), Vasey et al., (2020), Tye et al., (2020), Trexler et al., (2022), and Forte et al., (2022).

Figure 9 - Detrital zircon populations for 7 new Kura Fold-Thrust Belt samples. Setup of figure is identical to Figure 8. DZ populations are grouped by stratigraphic section to ease comparison between the tops and bottom of sections. Alternative version of this figure with PDPs/KDEs stacked by approximate stratigraphic age is presented in Figure S15.

Figure 10 - Results of Bayesian population correlation (Tye et al., 2019) between KFTB samples and composite sources. Red boxes indicate composite source and KFTB sample with the highest

similarity based on BPC, thick black outlines indicate comparisons between samples from the top and bottom of individual sections; note that these BPC values are relatively high, indicating minimal up-section changes in DZ-derived provenance. To minimize bias, samples V-1240 and S-210 were modified (indicated by *) by removing the young populations of grains that define the MDAs, see text for explanation. Source terranes abbreviations are as follows: GCSL – GC siliciclastic, GCB – GC basement, PJS – Pre-Jurassic sedimentary, WGCV – western GC volcaniclastics, EGCV- eastern GC volcaniclastics, TBLC – Transcaucasus basement and LC arc, and EUI- Eurasian interior. Red boxes indicate composite source and KFTB sample with the highest similarity based on BPC.

Figure 11 - Comparisons between linear discriminant analyses of bulk geochemistry and Bayesian population correlation of detrital zircon populations. We consider BPC values for the eastern GC volcaniclastic (EGCV), GC siliciclastic strata (GCSL), and Transcaucasus basement and LC arc (TBLC) sources, as these are the best represented in the KFTB sandstones. For each example, the vertical grey bars mark the range covered by the relevant decision boundaries within the first linear discriminant (see Figure 6 and S14). Comparison of linear discriminant 1 from LDA-1 (panels a-c) or LDA-2 (panels d-f) with BPCs from a/d) the eastern GC volcaniclastic source (EGCV), b/e) the GC siliciclastic source (GCSL), and c/f) the Transcaucasus basement and LC arc source (TBLC).

Figure 12 - Summary of provenance changes through time and space as indicated by both geochemistry and detrital zircons during a) Meotian-Pontian, b) Productive Series, c) Akchagylian, d) Apsheronian, and e) Bakunian stages. Vertical colored columns for each section represent the two possible interpretations of provenance from the LDA classification of the trace element geochemistry for the portion of the stratigraphy within a given time period. Stars indicate DZ samples, either those that come from the measured sections (those adjacent to the LDA results) or from areas further afield within the KFTB from Tye et al., (2020). See explanation in bottom right for the correspondence between colors and sources. Stars containing more than one color indicate inferred mixed sources. Map is focused on central KFTB samples and sections, but results from samples from Tye et al., (2020) outside of this region are shown schematically, with original sample names from Tye et al., (2020) above each. Grayed out section locations indicate a lack of data for that time period from that section. Note that this map is not palinspastic and does not reflect that the distances between sections and the GC or LC rangefronts would have been different at the time of deposition.

Figure 13 - Schematic cross-sections through the central KFTB during the a) Productive Series, b) Akchagylian-Apsheronian boundary, and c) Apsheronian-Bakunian boundary. Diagram is not to scale, but we schematically depict advection of the sections toward the GC via continued underthrusting and reduction in distance between sections as KFTB structures initiate and accommodate shortening. Grayed out section locations indicate there is no data for that time from that section. Approximate location of Bozdagh (B), Xocashen (X), and Sarica (S) measured sections are shown. Blue colors indicate flysh sources or stratigraphy that appears to be

sourced from flysch, green colors indicate volcanic/volcaniclastic sources, and orange indicate sourcing from the mixed GC and LC as seen in Bozdagh or the modern Kura River. The concentric circle indicates approximate location of axial drainage (Kura River).

TABLE CAPTIONS

Table 1 – Coordinates of top and bottom the measured sections.

Table 2 – Coordinates of provenance samples including original sample names, sample names used in the manuscript, and the analyses performed (G – bulk geochemistry, PC – petrography, DZ – detrital zircon U-Pb geochronology).

Table 3 – Coordinates of ash samples and means and standard deviations of major elements of the ash shards extracted from the ash samples.

Table 4 – Samples and references for those samples used to define composite DZ sources

Table 5 – Perkins statistical distance between ash samples from within measured sections

Table 6 – LDA values for source samples and resultant source designations.

Table 7 – LDA values for KFTB samples and resultant source classifications.

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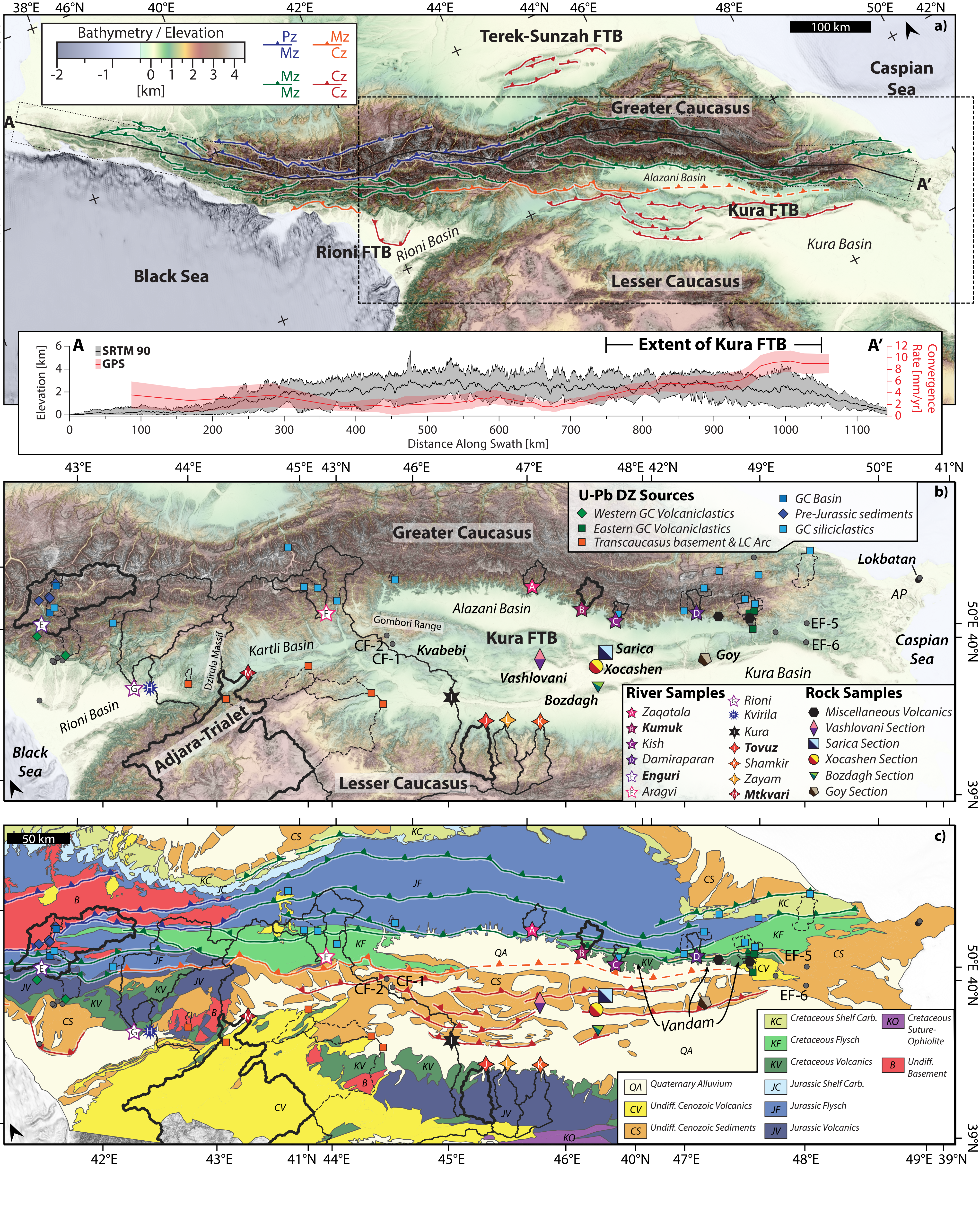
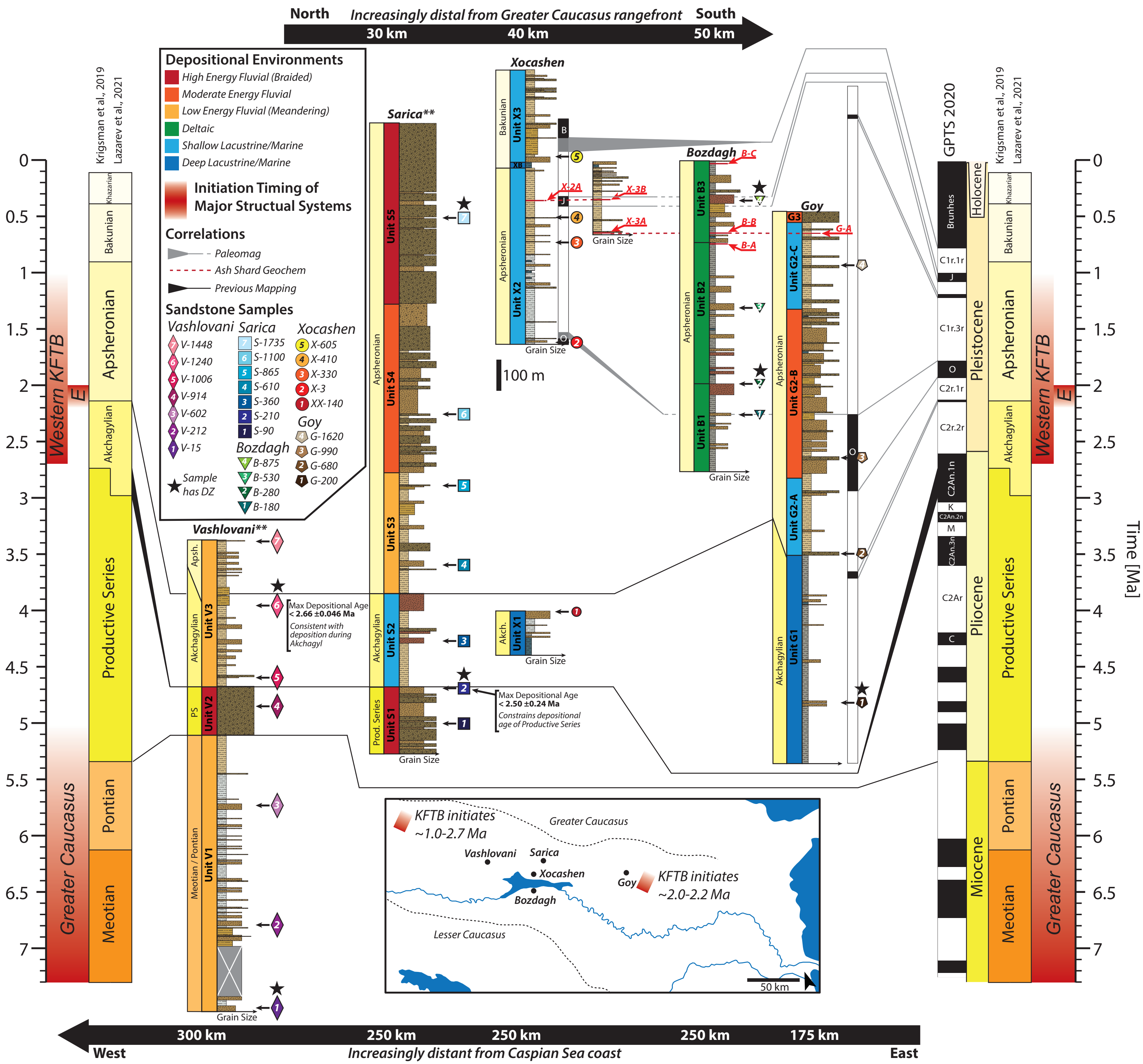
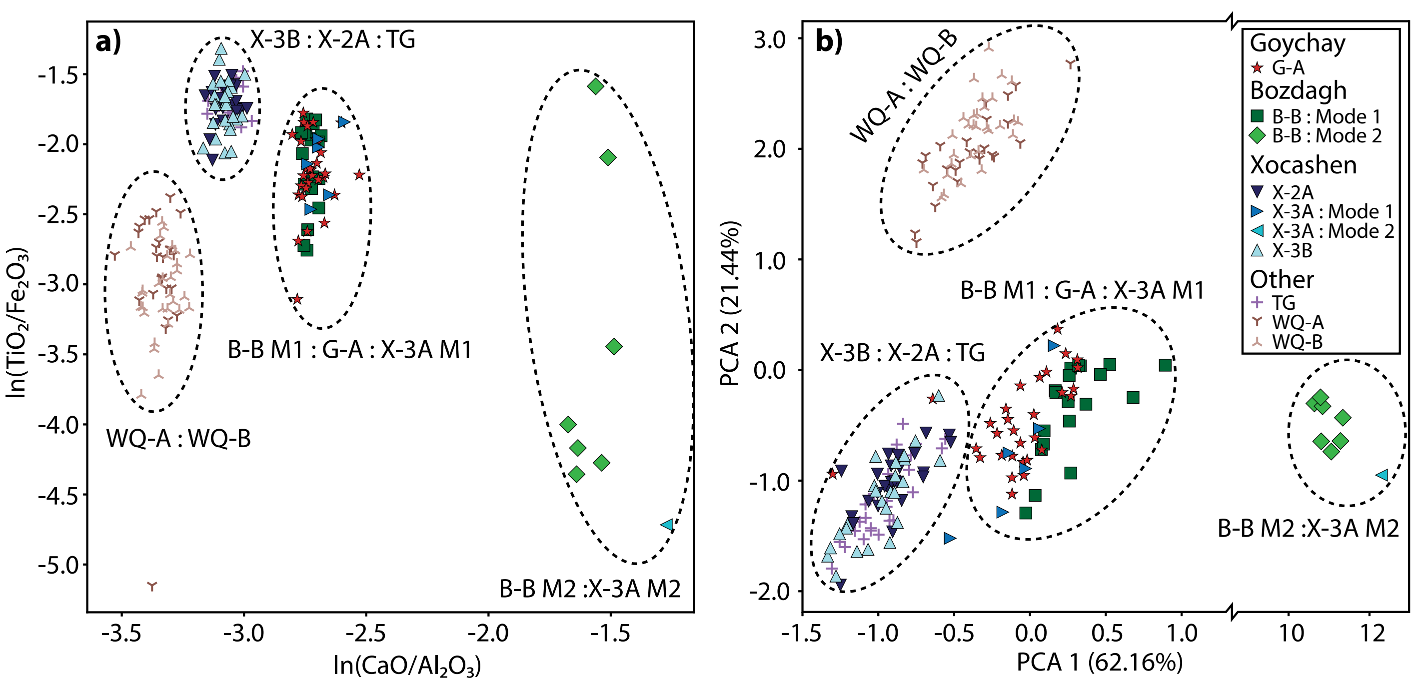


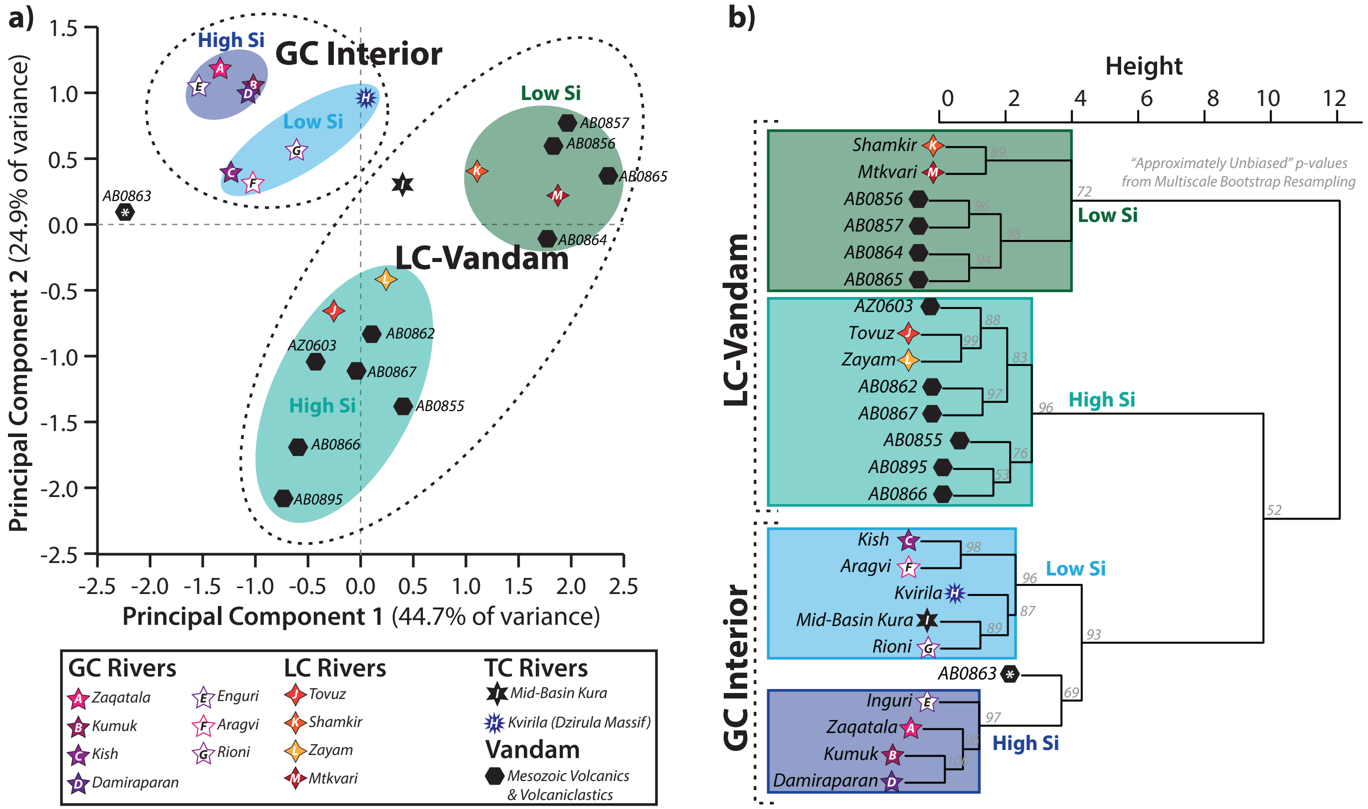
a)
Bathymetry / Elevation
-2 -1 0 1 2 3 4
[km]
Pz Mz
Mz Cz
Mz Mz
Cz Cz
100 km
Terek-Sunzah FTB
Caspian Sea
Greater Caucasus
A
A'
Alazani Basin
Kura FTB
Kura Basin
Rioni FTB
Rioni Basin
Black Sea
Lesser Caucasus
SRTM 90
GPS
Extent of Kura FTB
Elevation [km]
Convergence Rate [mm/yr]
Distance Along Swath [km]
b)
U-Pb DZ Sources
Western GC Volcaniclastics
Eastern GC Volcaniclastics
Transcaucasus basement & LC Arc
GC Basin
Pre-Jurassic sediments
GC siliciclastics
Greater Caucasus
Lokbatan
AP
Alazani Basin
Gombori Range
Kartli Basin
Dzirula Massif
Kvabebi
Kura FTB
Sarica
Xocashen
Goy
Vashlovani
Bozdagh
Kura Basin
EF-5
EF-6
CF-2
CF-1
Caspian Sea
Rioni Basin
Adjara-Trialet
Black Sea
Lesser Caucasus
River Samples
Zaqatala
Kumuk
Kish
Damiraparan
Enguri
Aragvi
Rioni
Kvirila
Kura
Tovuz
Shamkir
Zayam
Mtkvari
Rock Samples
Miscellaneous Volcanics
Vashlovani Section
Sarica Section
Xocashen Section
Bozdagh Section
Goy Section
c)
50 km
Vandam
QA Quaternary Alluvium
CV Undiff. Cenozoic Volcanics
CS Undiff. Cenozoic Sediments
KC Cretaceous Shelf Carb.
KF Cretaceous Flysch
KV Cretaceous Volcanics
JC Jurassic Shelf Carb.
JF Jurassic Flysch
JV Jurassic Volcanics
KO Cretaceous Suture-Ophiolite
B Undiff. Basement



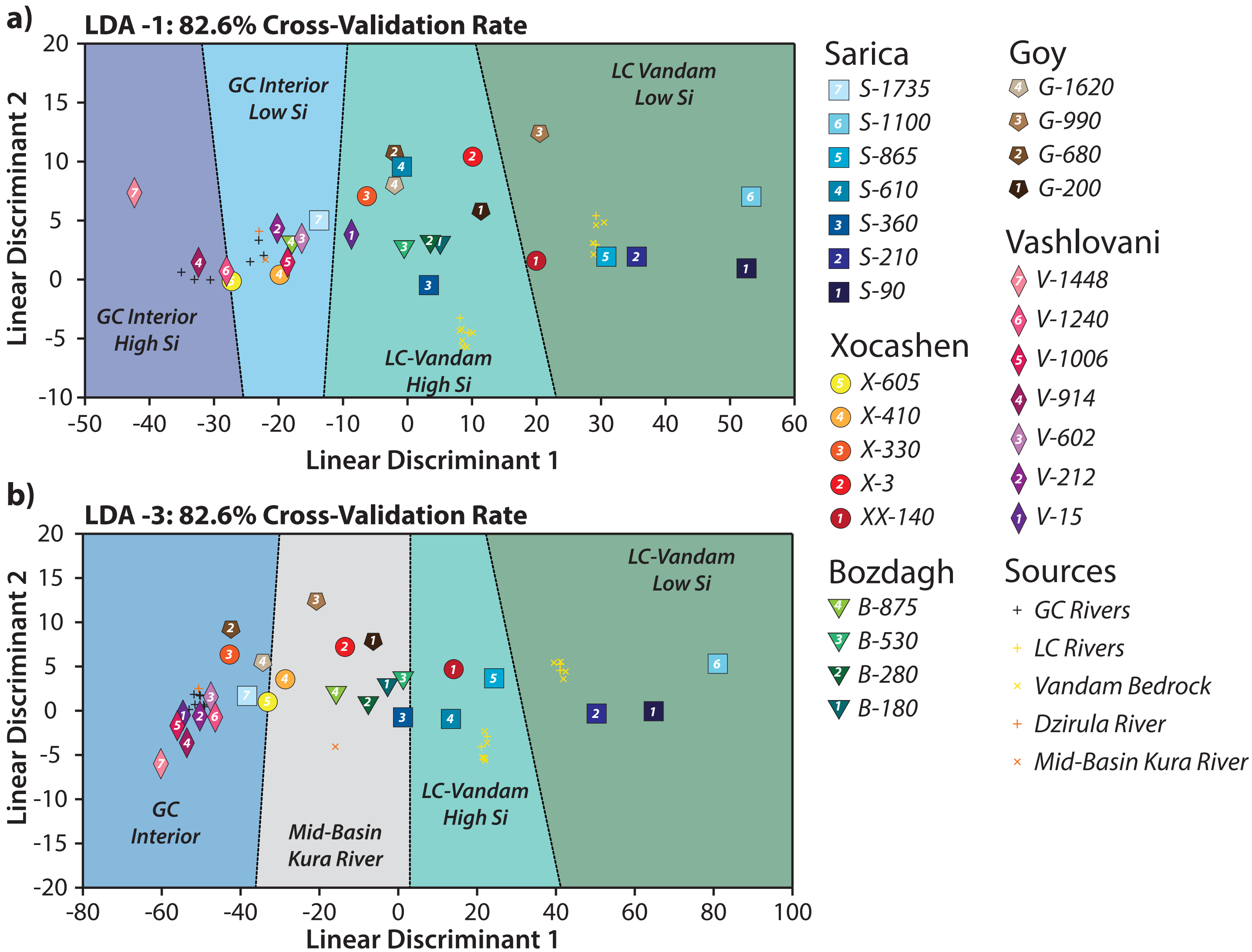
North
Increasingly distal from Greater Caucasus rangefront
South
30 km
40 km
50 km
Depositional Environments
High Energy Fluvial (Braided)
Moderate Energy Fluvial
Low Energy Fluvial (Meandering)
Deltaic
Shallow Lacustrine/Marine
Deep Lacustrine/Marine
Initiation Timing of Major Structual Systems
Correlations
Paleomag
Ash Shard Geochem
Previous Mapping
Sandstone Samples
Vashlovani
Sarica
Xocashen
Goy
Bozdagh
Sample has DZ
Xocashen
Sarica**
Bozdagh
Goy
Vashlovani**
Grain Size
100 m
Max Depositional Age < 2.66 ±0.046 Ma
Consistent with deposition during Akchagyl
Max Depositional Age < 2.50 ±0.24 Ma
Constrains depositional age of Productive Series
GPTS 2020
Krigsman et al., 2019
Lazarev et al., 2021
Western KFTB
Greater Caucasus
Khazarian
Bakunian
Apsheronian
Akchagylian
Productive Series
Pontian
Meotian
Holocene
Pleistocene
Pliocene
Miocene
Time [Ma]
KFTB initiates ~1.0-2.7 Ma
KFTB initiates ~2.0-2.2 Ma
Greater Caucasus
Lesser Caucasus
Vashlovani
Sarica
Xocashen
Bozdagh
Goy
50 km
300 km
250 km
250 km
250 km
175 km
West
Increasingly distant from Caspian Sea coast
East



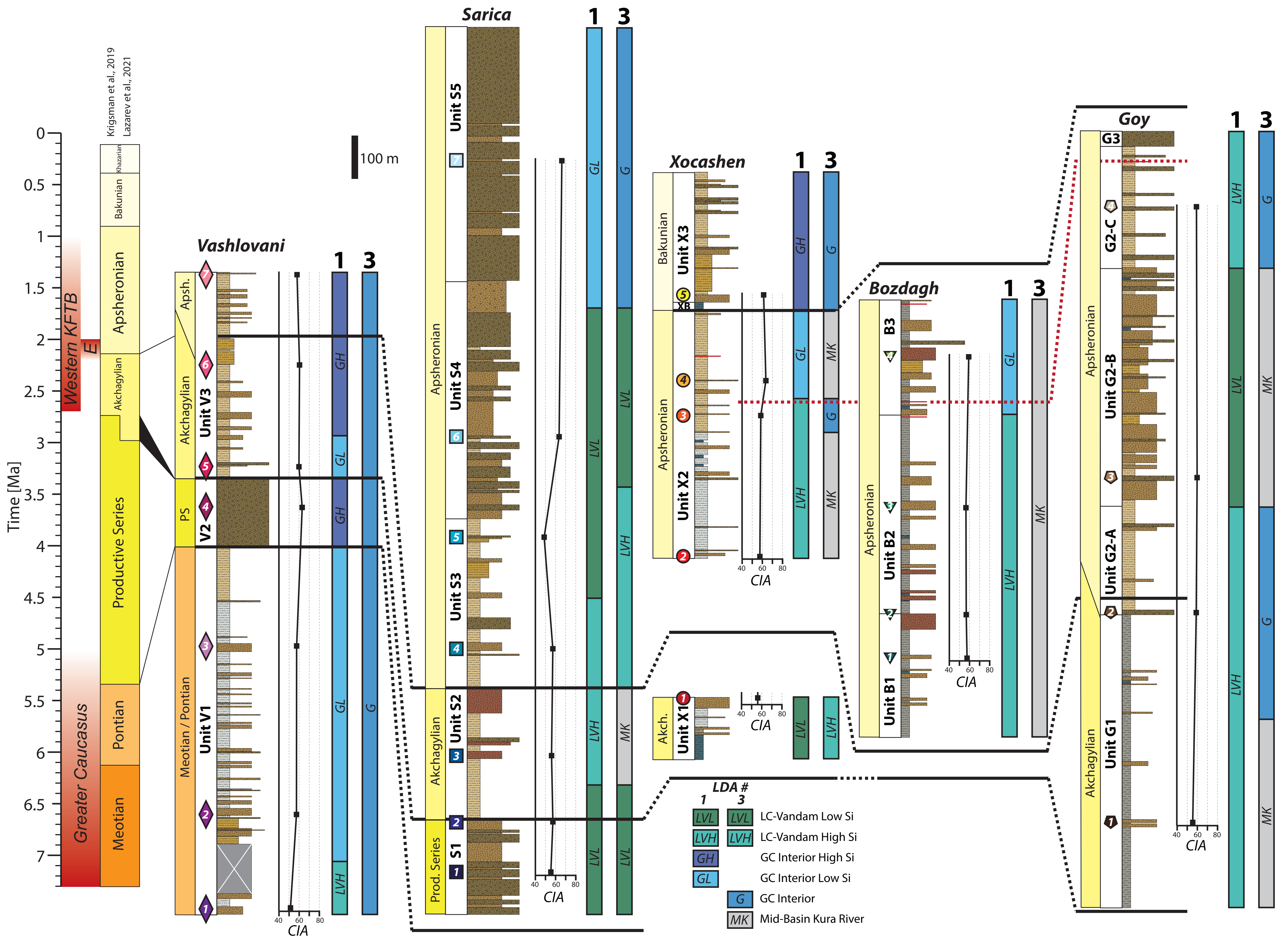
a)
X-3B : X-2A : TG
B-B M1 : G-A : X-3A M1
WQ-A : WQ-B
B-B M2 :X-3A M2
ln(TiO2/Fe2O3)
ln(CaO/Al2O3)
b)
WQ-A : WQ-B
B-B M1 : G-A : X-3A M1
X-3B : X-2A : TG
B-B M2 :X-3A M2
PCA 2 (21.44%)
PCA 1 (62.16%)
Goychay
G-A
Bozdagh
B-B : Mode 1
B-B : Mode 2
Xocashen
X-2A
X-3A : Mode 1
X-3A : Mode 2
X-3B
Other
TG
WQ-A
WQ-B



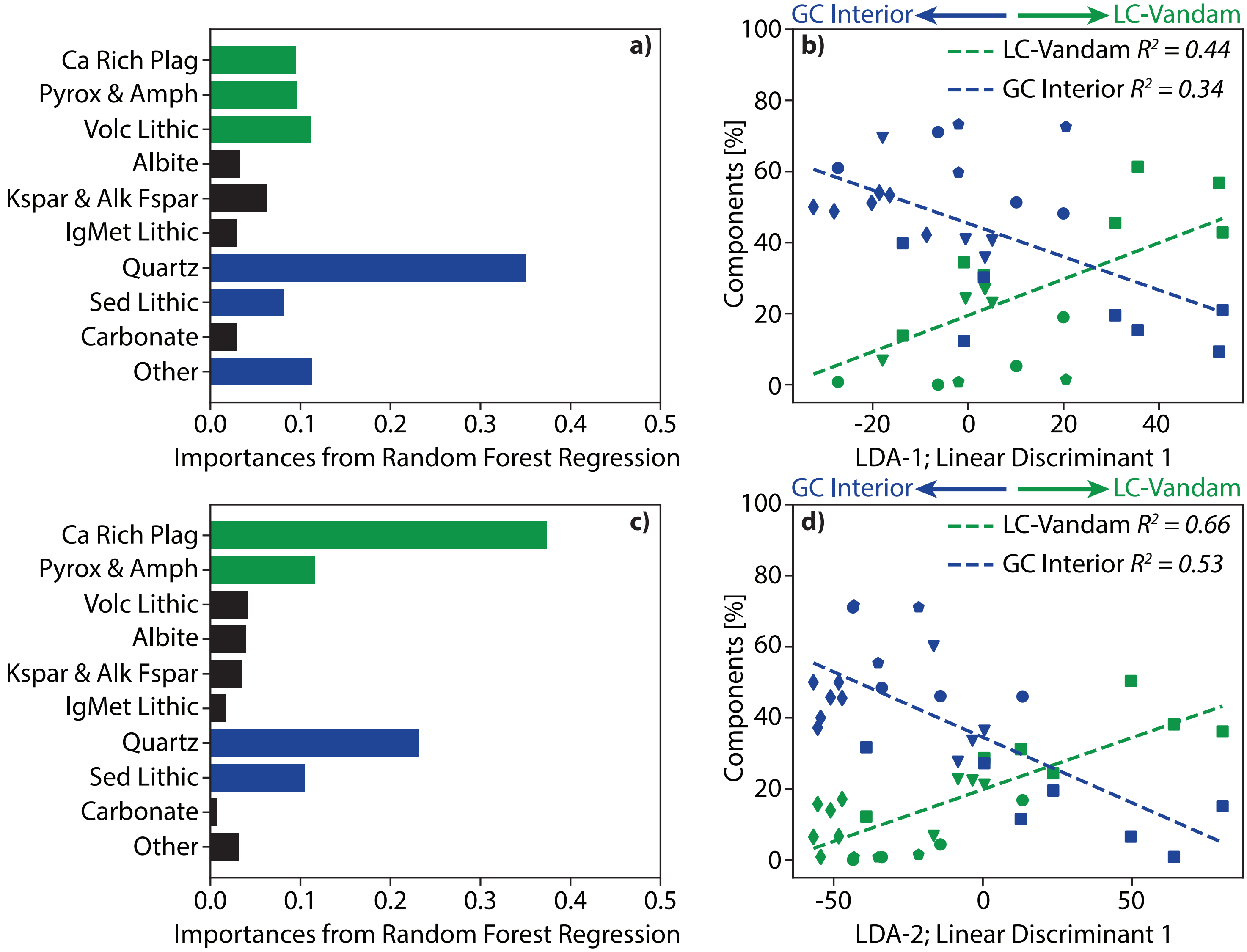
a)
GC Interior
High Si
Low Si
Low Si
LC-Vandam
High Si
AB0863
AB0857
AB0856
AB0865
AB0864
AB0862
AZ0603
AB0867
AB0855
AB0866
AB0895
Principal Component 2 (24.9% of variance)
Principal Component 1 (44.7% of variance)
GC Rivers
Zaqatala
Kumuk
Kish
Damiraparan
Enguri
Aragvi
Rioni
LC Rivers
Tovuz
Shamkir
Zayam
Mtkvari
TC Rivers
Mid-Basin Kura
Kvirila (Dzirula Massif)
Vandam
Mesozoic Volcanics & Volcaniclastics
b)
Height
"Approximately Unbiased" p-values from Multiscale Bootstrap Resampling
LC-Vandam
GC Interior
Shamkir
Mtkvari
AB0856
AB0857
AB0864
AB0865
Low Si
AZ0603
Tovuz
Zayam
AB0862
AB0867
AB0855
AB0895
AB0866
High Si
Kish
Aragvi
Kvirila
Mid-Basin Kura
Rioni
Low Si
AB0863
Inguri
Zaqatala
Kumuk
Damiraparan
High Si



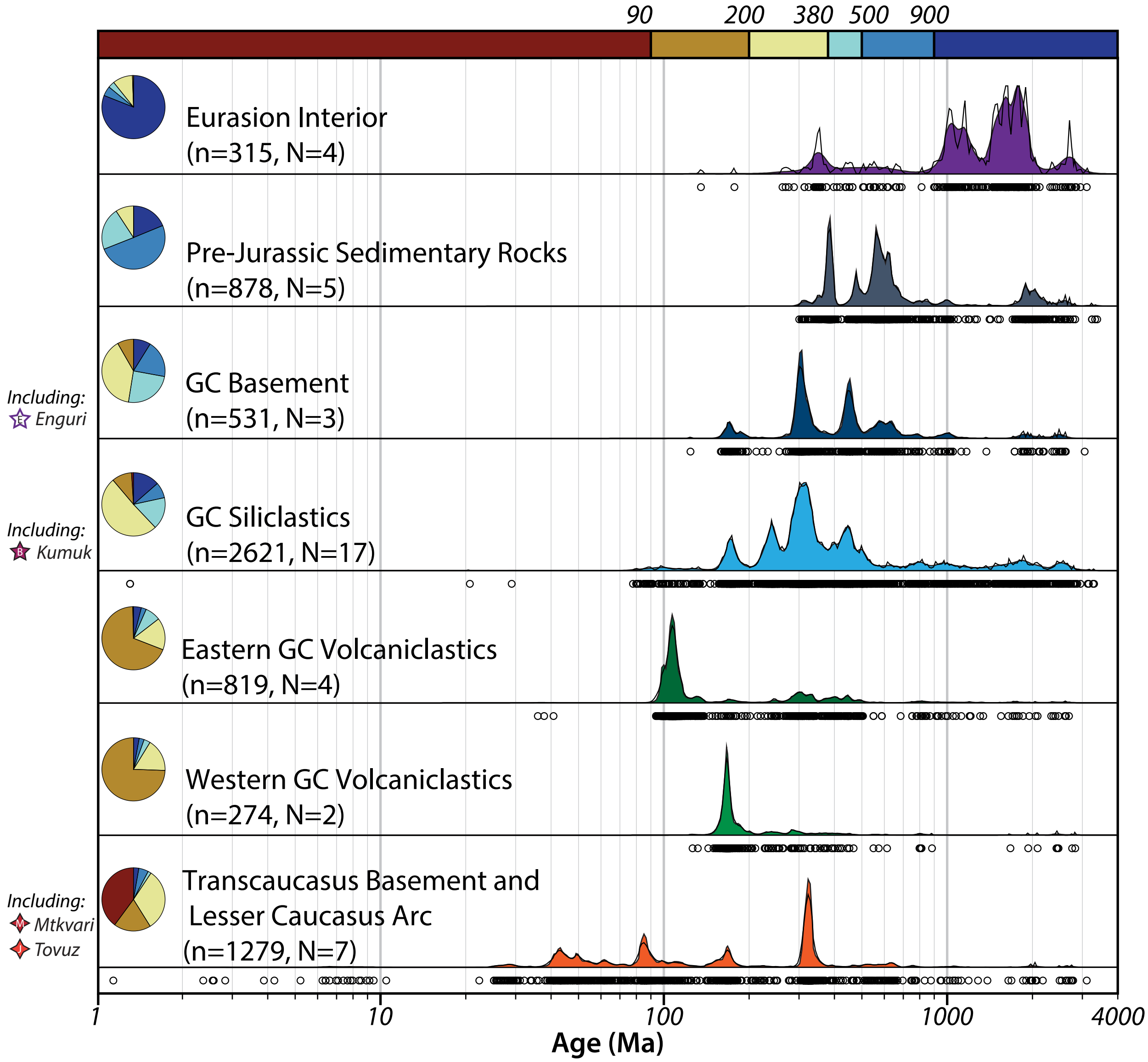
a)
LDA -1: 82.6% Cross-Validation Rate
GC Interior Low Si
LC Vandam Low Si
GC Interior High Si
LC-Vandam High Si
Linear Discriminant 1
Linear Discriminant 2
b)
LDA -3: 82.6% Cross-Validation Rate
LC-Vandam Low Si
GC Interior
Mid-Basin Kura River
LC-Vandam High Si
Linear Discriminant 1
Linear Discriminant 2
Sarica
S-1735
S-1100
S-865
S-610
S-360
S-210
S-90
Goy
G-1620
G-990
G-680
G-200
Xocashen
X-605
X-410
X-330
X-3
XX-140
Vashlovani
V-1448
V-1240
V-1006
V-914
V-602
V-212
V-15
Bozdagh
B-875
B-530
B-280
B-180
Sources
GC Rivers
LC Rivers
Vandam Bedrock
Dzirula River
Mid-Basin Kura River

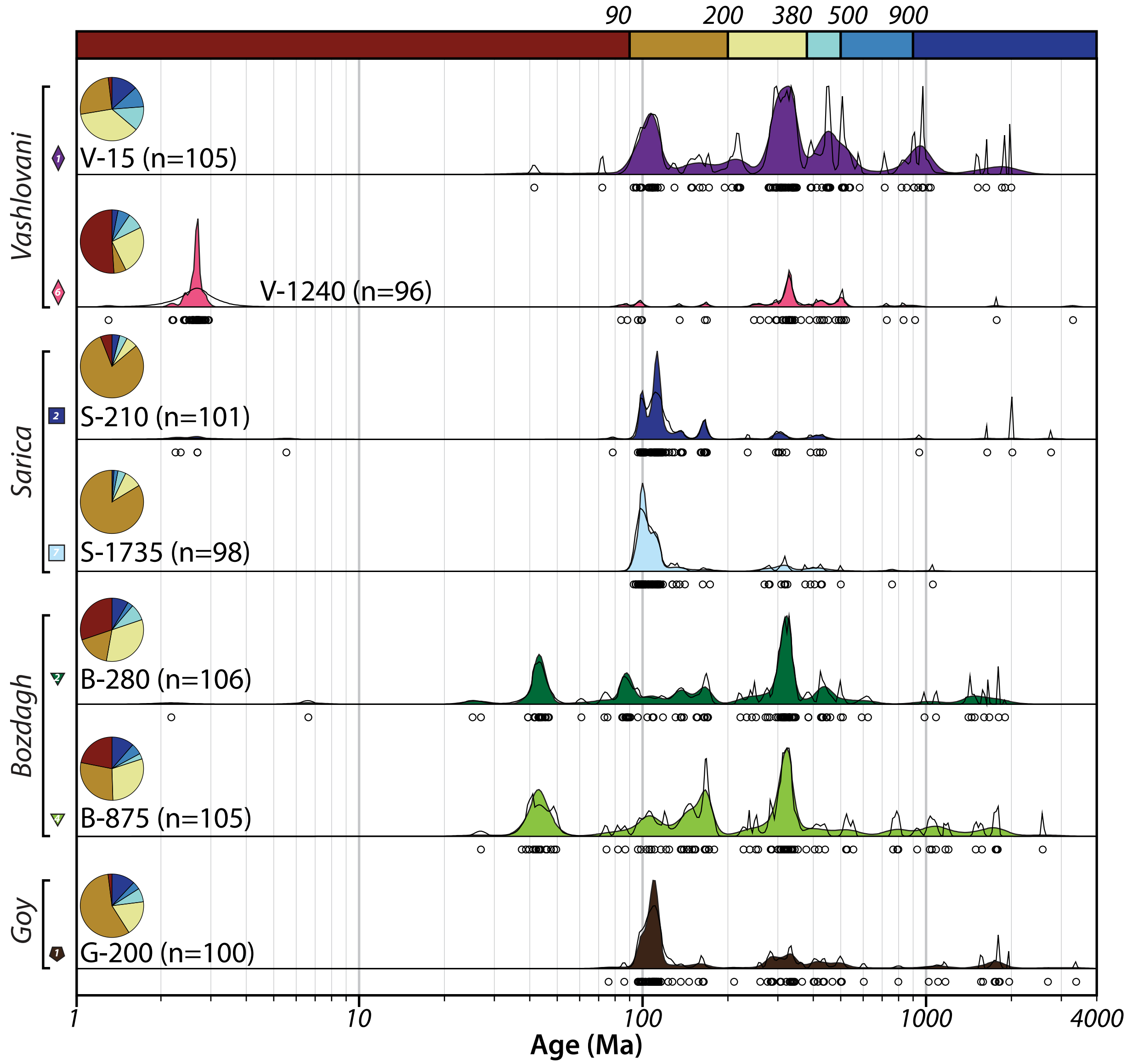


Krigsman et al., 2019
Lazarev et al., 2021
Time [Ma]
Western KFTB
E
Greater Caucasus
Khazarian
Bakunian
Apsheronian
Akchagylian
Productive Series
Pontian
Meotian
100 m
Vashlovani
Sarica
Xocashen
Bozdagh
Goy
Apsh.
Akchagylian
Unit V3
PS
V2
Meotian / Pontian
Unit V1
Unit S5
Unit S4
Unit S3
Apsheronian
Akchagylian
Unit S2
Prod. Series
S1
Bakunian
Unit X3
XB
Apsheronian
Unit X2
Akch.
Unit X1
B3
Unit B2
Unit B1
G3
G2-C
Unit G2-B
Unit G2-A
Unit G1
CIA
LDA #
LC-Vandam Low Si
LC-Vandam High Si
GC Interior High Si
GC Interior Low Si
GC Interior
Mid-Basin Kura River

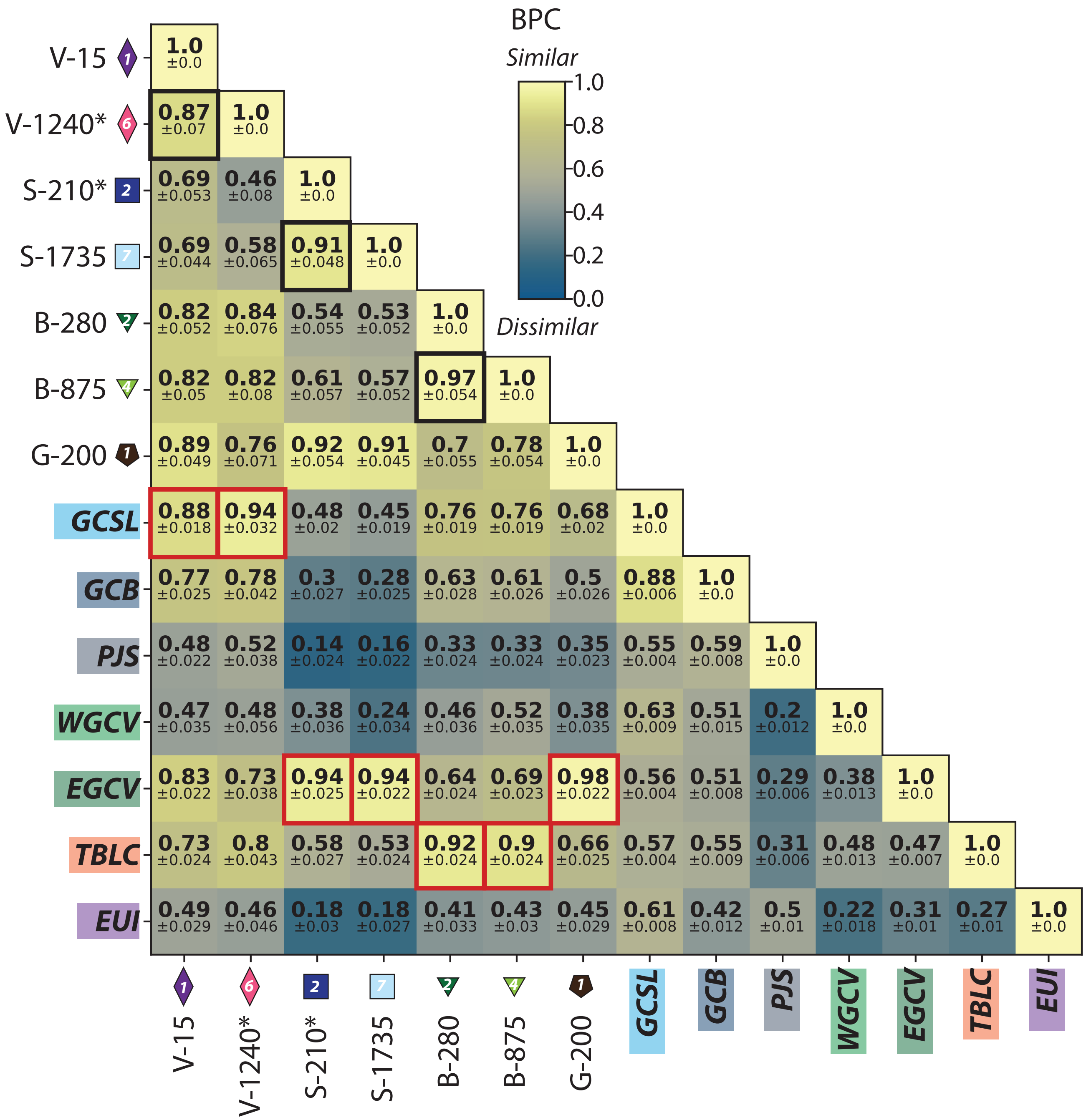


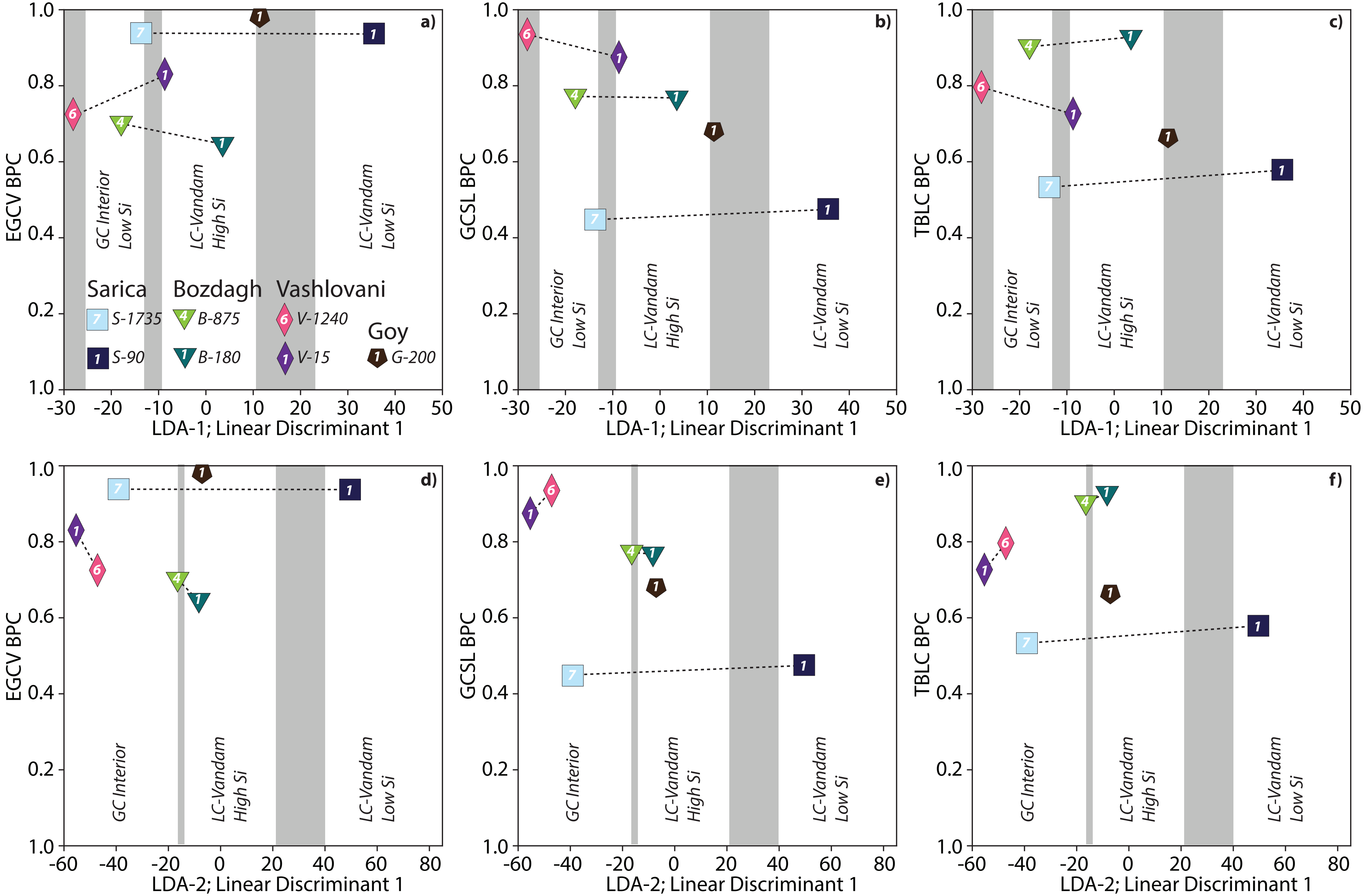
a)
Ca Rich Plag
Pyrox & Amph
Volc Lithic
Albite
Kspar & Alk Fspar
IgMet Lithic
Quartz
Sed Lithic
Carbonate
Other
0.0 0.1 0.2 0.3 0.4 0.5
Importances from Random Forest Regression
b)
GC Interior
LC-Vandam
LC-Vandam $R^2 = 0.44$
GC Interior $R^2 = 0.34$
Components [%]
0 20 40 60 80 100
-20 0 20 40
LDA-1; Linear Discriminant 1
c)
Ca Rich Plag
Pyrox & Amph
Volc Lithic
Albite
Kspar & Alk Fspar
IgMet Lithic
Quartz
Sed Lithic
Carbonate
Other
0.0 0.1 0.2 0.3 0.4 0.5
Importances from Random Forest Regression
d)
GC Interior
LC-Vandam
LC-Vandam $R^2 = 0.66$
GC Interior $R^2 = 0.53$
Components [%]
0 20 40 60 80 100
-50 0 50
LDA-2; Linear Discriminant 1


90
200
380
500
900
Eurasion Interior
(n=315, N=4)
Pre-Jurassic Sedimentary Rocks
(n=878, N=5)
Including:
Enguri
GC Basement
(n=531, N=3)
Including:
Kumuk
GC Siliclastics
(n=2621, N=17)
Eastern GC Volcaniclastics
(n=819, N=4)
Western GC Volcaniclastics
(n=274, N=2)
Including:
Mtkvari
Tovuz
Transcaucasus Basement and
Lesser Caucasus Arc
(n=1279, N=7)
1
10
100
1000
4000
Age (Ma)

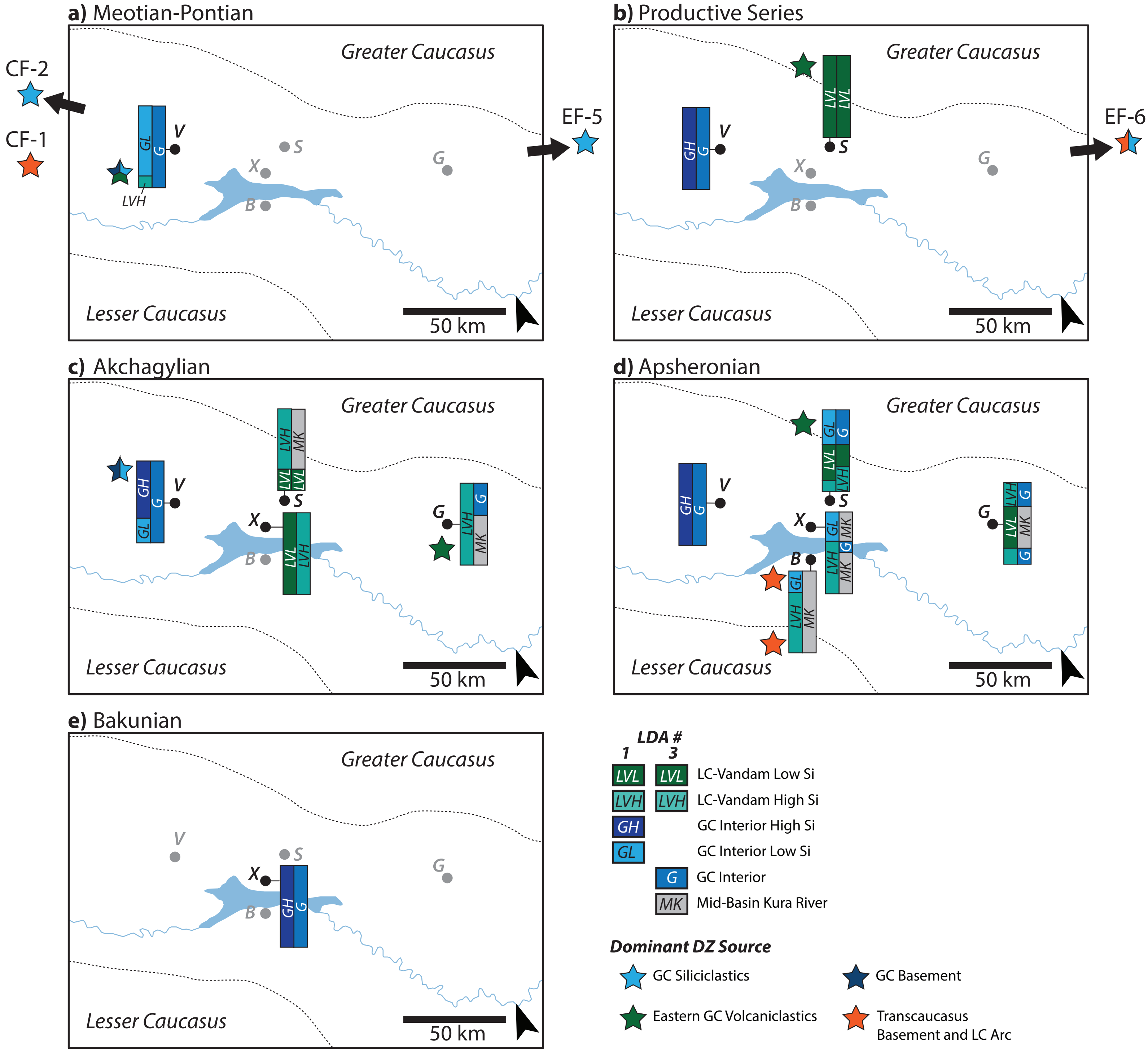


90
200
380
500
900
Vashlovani
V-15 (n=105)
V-1240 (n=96)
Sarica
S-210 (n=101)
S-1735 (n=98)
Bozdagh
B-280 (n=106)
B-875 (n=105)
Goy
G-200 (n=100)
1
10
100
1000
4000
Age (Ma)

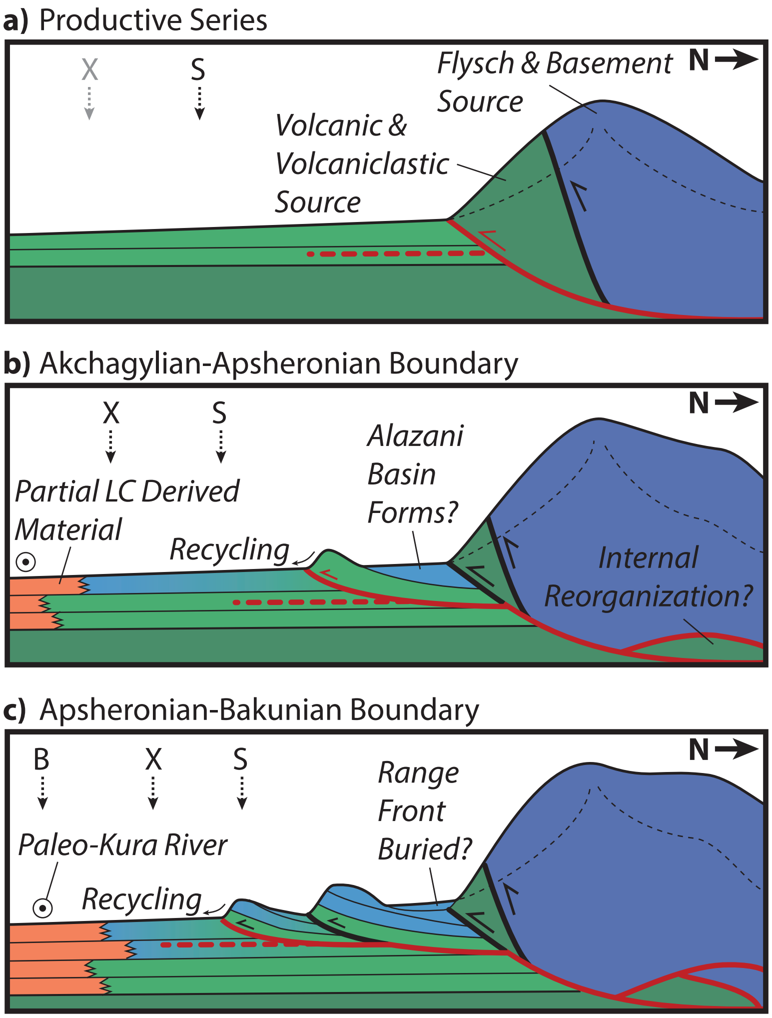

BPC
Similar
1.0
0.8
0.6
0.4
0.2
0.0
Dissimilar
V-15 1
V-1240* 6
S-210* 2
S-1735 7
B-280 2
B-875 4
G-200 1
GCSL
GCB
PJS
WGCV
EGCV
TBLC
EUI
1.0 ±0.0
0.87 ±0.07 1.0 ±0.0
0.69 ±0.053 0.46 ±0.08 1.0 ±0.0
0.69 ±0.044 0.58 ±0.065 0.91 ±0.048 1.0 ±0.0
0.82 ±0.052 0.84 ±0.076 0.54 ±0.055 0.53 ±0.052 1.0 ±0.0
0.82 ±0.05 0.82 ±0.08 0.61 ±0.057 0.57 ±0.052 0.97 ±0.054 1.0 ±0.0
0.89 ±0.049 0.76 ±0.071 0.92 ±0.054 0.91 ±0.045 0.7 ±0.055 0.78 ±0.054 1.0 ±0.0
0.88 ±0.018 0.94 ±0.032 0.48 ±0.02 0.45 ±0.019 0.76 ±0.019 0.76 ±0.019 0.68 ±0.02 1.0 ±0.0
0.77 ±0.025 0.78 ±0.042 0.3 ±0.027 0.28 ±0.025 0.63 ±0.028 0.61 ±0.026 0.5 ±0.026 0.88 ±0.006 1.0 ±0.0
0.48 ±0.022 0.52 ±0.038 0.14 ±0.024 0.16 ±0.022 0.33 ±0.024 0.33 ±0.024 0.35 ±0.023 0.55 ±0.004 0.59 ±0.008 1.0 ±0.0
0.47 ±0.035 0.48 ±0.056 0.38 ±0.036 0.24 ±0.034 0.46 ±0.036 0.52 ±0.035 0.38 ±0.035 0.63 ±0.009 0.51 ±0.015 0.2 ±0.012 1.0 ±0.0
0.83 ±0.022 0.73 ±0.038 0.94 ±0.025 0.94 ±0.022 0.64 ±0.024 0.69 ±0.023 0.98 ±0.022 0.56 ±0.004 0.51 ±0.008 0.29 ±0.006 0.38 ±0.013 1.0 ±0.0
0.73 ±0.024 0.8 ±0.043 0.58 ±0.027 0.53 ±0.024 0.92 ±0.024 0.9 ±0.024 0.66 ±0.025 0.57 ±0.004 0.55 ±0.009 0.31 ±0.006 0.48 ±0.013 0.47 ±0.007 1.0 ±0.0
0.49 ±0.029 0.46 ±0.046 0.18 ±0.03 0.18 ±0.027 0.41 ±0.033 0.43 ±0.03 0.45 ±0.029 0.61 ±0.008 0.42 ±0.012 0.5 ±0.01 0.22 ±0.018 0.31 ±0.01 0.27 ±0.01 1.0 ±0.0
V-15
V-1240*
S-210*
S-1735
B-280
B-875
G-200
GCSL
GCB
PJS
WGCV
EGCV
TBLC
EUI



a)
b)
c)
d)
e)
f)
EGCV BPC
GCSL BPC
TBLC BPC
LDA-1; Linear Discriminant 1
LDA-2; Linear Discriminant 1
GC Interior Low Si
LC-Vandam High Si
LC-Vandam Low Si
GC Interior
Sarica
Bozdagh
Vashlovani
Goy
S-1735
S-90
B-875
B-180
V-1240
V-15
G-200



a) Meotian-Pontian
b) Productive Series
c) Akchagylian
d) Apsheronian
e) Bakunian
Greater Caucasus
Lesser Caucasus
50 km
CF-2
CF-1
EF-5
EF-6
V
S
X
B
G
GL
GH
LVL
LVH
MK
LDA #
1
3
LVL LVL LC-Vandam Low Si
LVH LVH LC-Vandam High Si
GH GC Interior High Si
GL GC Interior Low Si
G GC Interior
MK Mid-Basin Kura River
Dominant DZ Source
GC Siliciclastics
GC Basement
Eastern GC Volcaniclastics
Transcaucasus Basement and LC Arc


a) Productive Series
X
S
Flysch & Basement Source
N
Volcanic & Volcaniclastic Source
b) Akchagylian-Apsheronian Boundary
X
S
N
Alazani Basin Forms?
Partial LC Derived Material
Recycling
Internal Reorganization?
c) Apsheronian-Bakunian Boundary
B
X
S
N
Range Front Buried?
Paleo-Kura River
Recycling